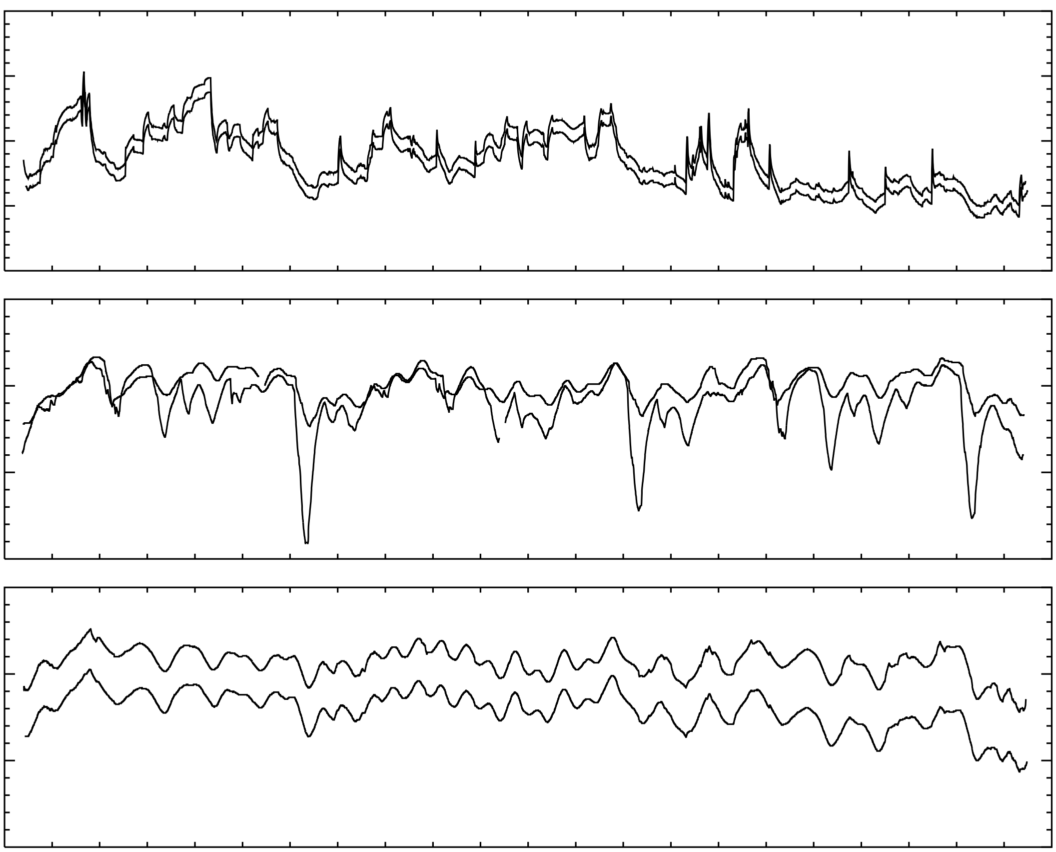
Assessment of the Fresh- and Brackish-Water Resources Underlying Dunedin and Adjacent Areas of Northern Pinellas County, Florida

U.S. Geological Survey

Water-Resources Investigations Report 96–4164

Prepared in cooperation with the

City of Dunedin and the
Southwest Florida Water Management District



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By Lari A. Knochenmus and E.S. Swenson

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CITY OF DUNEDIN and the
SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

Tallahassee, Florida
1996

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VERTICAL DATUM, ACRONYMNS, AND ABBREVIATIONS

<u>Sea level</u>: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) -- a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

mi^2	=	square mile
ft	=	feet
ft^2	=	square feet
ft/d	=	feet per day
(ft/d)/ft	=	feet per day per foot
ft^2/d	=	feet squared per day
in	=	inch
Mgal/d	=	million gallons per day
gal/min	=	gallons per minute
mg/L	=	milligrams per liter
DS	=	dissolved solids
lb/in^2	=	pounds per square inch
SAS	=	surficial aquifer system
ICU	=	intermediate confining unit
UFA	=	Upper Floridan aquifer
LFA	=	Lower Floridan aquifer
UZA	=	upper zone A
LZA	=	lower zone A
SCU	=	semiconfining unit
ROMP	=	Regional Observation and Monitoring Well Program
SWFWMD	=	Southwest Florida Water Management District
USGS	=	United States Geological Survey
HST3D	=	Heat and Solute Transport in 3 Dimensions

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Abstract

The city of Dunedin is enhancing their potable ground-water resources through desalination of brackish ground water. An assessment of the fresh- and brackish-water resources in the Upper Floridan aquifer was needed to estimate the changes that may result from brackish-water development. The complex hydrogeologic framework underlying Dunedin and adjacent areas of northern Pinellas County is conceptualized as a multilayered sequence of permeable zones and confining and semiconfining units. The permeable zones contain vertically spaced, discrete, water-producing zones with differing water quality. Water levels, water-level responses, and water quality are highly variable among the different permeable zones.

The Upper Floridan aquifer is best characterized as a local flow system in most of northern Pinellas County. Pumping from the Dunedin well field is probably not influencing water levels in the aquifer outside Dunedin, but has resulted in localized depressions in the potentiometric surface surrounding production-well clusters.

The complex geologic layering combined with the effects of production-well distribution probably contribute to the spatial and temporal variability in chloride concentrations in the Dunedin well field. Chloride concentrations in ground water underlying the Dunedin well field vary both vertically and laterally. In general, water-quality rapidly changes below depths of 400 feet below sea level. Additionally, randomly distributed water-producing zones with higher chloride concentrations may occur at shallow, discrete intervals above 400 feet. A relation between chloride concentration and distance from St. Joseph Sound is not apparent; however, a possible relation exists between chloride concentration and production-well density. Chloride-concentration data from production wells show a consistently increasing pattern that has accelerated since the late 1980's. Chloride-concentration data from 15 observation wells show increasing trends for 6 wells, decreasing trends for 3 wells, and no trend for 6 wells.

The current and future, fresh- and brackish-water resources were evaluated using a numerical ground-water flow and solute-transport model. Simulation results indicate that the hydraulic conductivity of the uppermost permeable zone (upper zone A) of the Upper Floridan aquifer is four times greater than the two underlying permeable zones (lower zone A and zone B). The simulated hydraulic conductivities of the semiconfining units are four orders of magnitude less than the permeable zones. Simulation results show the importance of semiconfining units as a mechanism for retarding the vertical movement of higher salinity ground water. Simulation results indicate that pumping from the brackish-water zone does not negatively influence the chloride-concentration trends in the overlying fresh-water zone; however, chloride changes in the fresh-water zone will continue to occur due to the continuation of current fresh-water withdrawals. Chloride changes in the brackish-water zone will occur from pumping brackish water.

INTRODUCTION

The city of Dunedin, and other coastal communities in Florida face special problems in developing and sustaining fresh ground-water resources. Historically, the city of Dunedin has obtained potable water from wells penetrating the uppermost part of the Upper Floridan aquifer underlying the city. The Dunedin well field provides potable water for inhabitants living in a 12-square-mile (mi^2) area. As population density increased, production in the well field also increased. Public supply demands for Dunedin are expected to increase from the 1994 average of 4.9 to 7.2 million gallons per day (Mgal/d) in the year 2020. Although ample supplies of ground water continue to be available, the ground-water quality is changing. These changes, caused by concentrated withdrawals within the well field, persist today. One method to enhance ground-water resources is through desalination of brackish ground water. To continue to provide potable water, Dunedin plans to develop the brackish-water resources underlying the city. Evaluation of the brackish-water resources required the delineation of the water-producing and water-quality zones within the hydrogeologic units underlying Dunedin.

In this report, the Upper Floridan aquifer is divided into three water-quality zones that generally coincide with the permeable zones: the fresh-water zone (upper zone A), the brackish-water zone (lower zone A), and the saline-water zone (zone B). The zones are defined by a range in concentration for dissolved solids (DS) and chlorides. The ranges in DS concentrations for the fresh-water, brackish-water, and saline-water zones are 0-500, 500-10,000, and greater than 10,000 milligrams per liter (mg/L), respectively. The ranges in chloride for the fresh-water, brackish-water, and saline-water zones are 0-250, 250-5,200, and greater than 5,200 mg/L, respectively.

Purpose and Scope

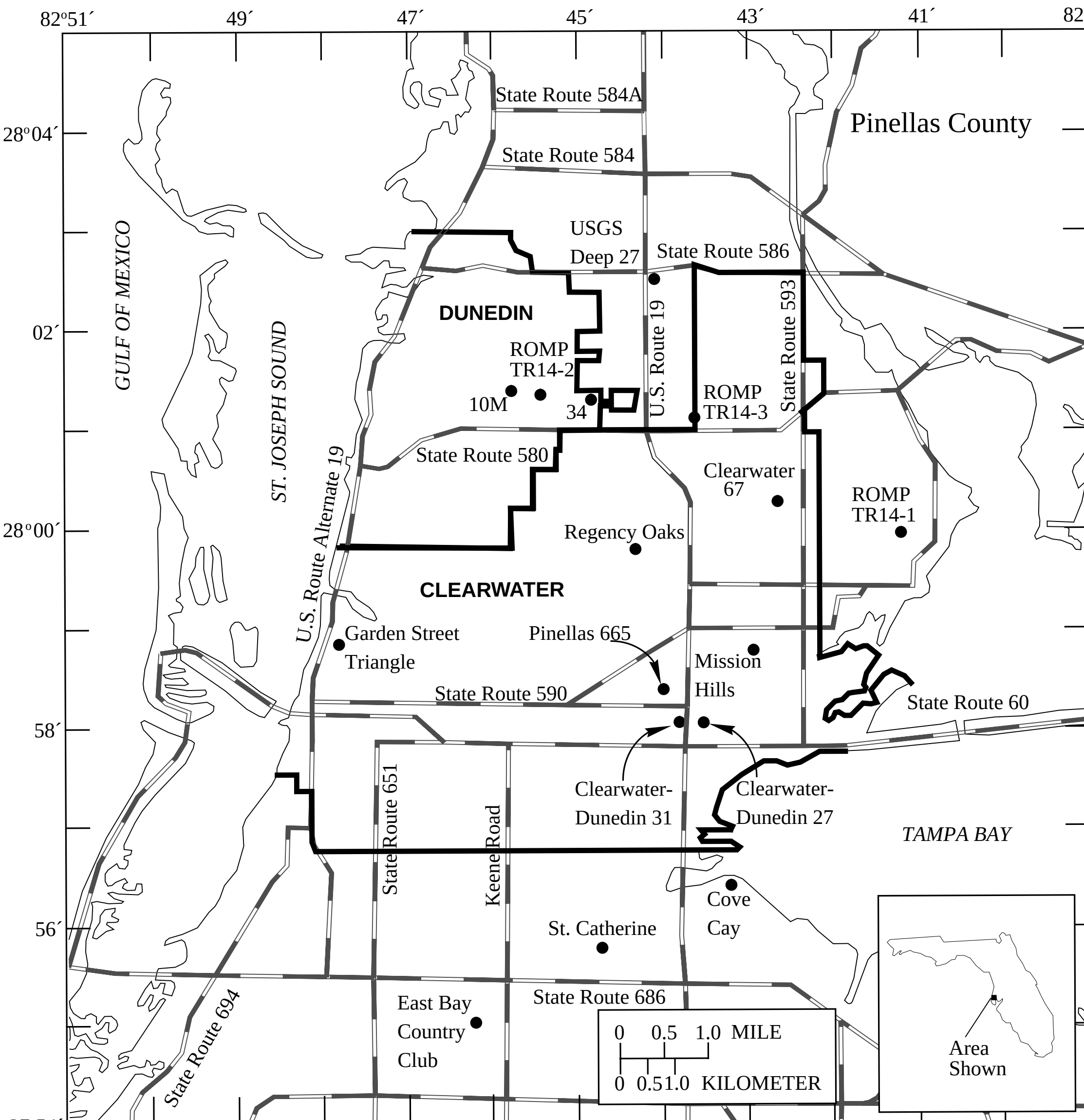
This report presents the results of a study initiated in 1993 by the U.S. Geological Survey (USGS), in cooperation with the city of Dunedin and the Southwest Florida Water Management District (SWFWMD), to assess the fresh- and brackish-water resources in the Upper Floridan aquifer underlying the city of Dunedin and adjacent areas of northern Pinellas County (figs. 1a and 1b). The report includes: descriptions of the hydrogeologic framework and geologic controls affecting the distribution of hydraulic characteristics and water quality in the heterogeneous, multilayered, multidensity aquifer system and discussions of the occurrence of ground water and aquifer testing in the study area. Simulation results are presented from a numerical ground-water flow and solute-transport model estimating current and future, fresh- and brackish-water resources near the Dunedin water plant.

Information presented in this report was obtained from data collected during this investigation, from unpublished reports on file at the USGS, and from published USGS, SWFWMD, and consultants' reports. Information collected during this investigation included lithologic and geophysical logs, water-quality, water-level, and aquifer-test data. Producing zone locations and their associated water quality were delineated using lithologic and geophysical logs and geochemical data collected during drilling of the brackish production and brackish monitor wells and from other Dunedin production and monitor wells. A conceptual model of the ground-water system and water-quality distribution was developed to: (1) organize the concepts of the physical and chemical system behavior, (2) provide an understanding of the ground-water flow and the water-quality changes resulting from simultaneous withdrawals from both the fresh-water producing zone (upper zone A) and brackish-water producing zone (lower zone A), and (3) relate these concepts to the framework of the numerical model.

Description of the Study Area

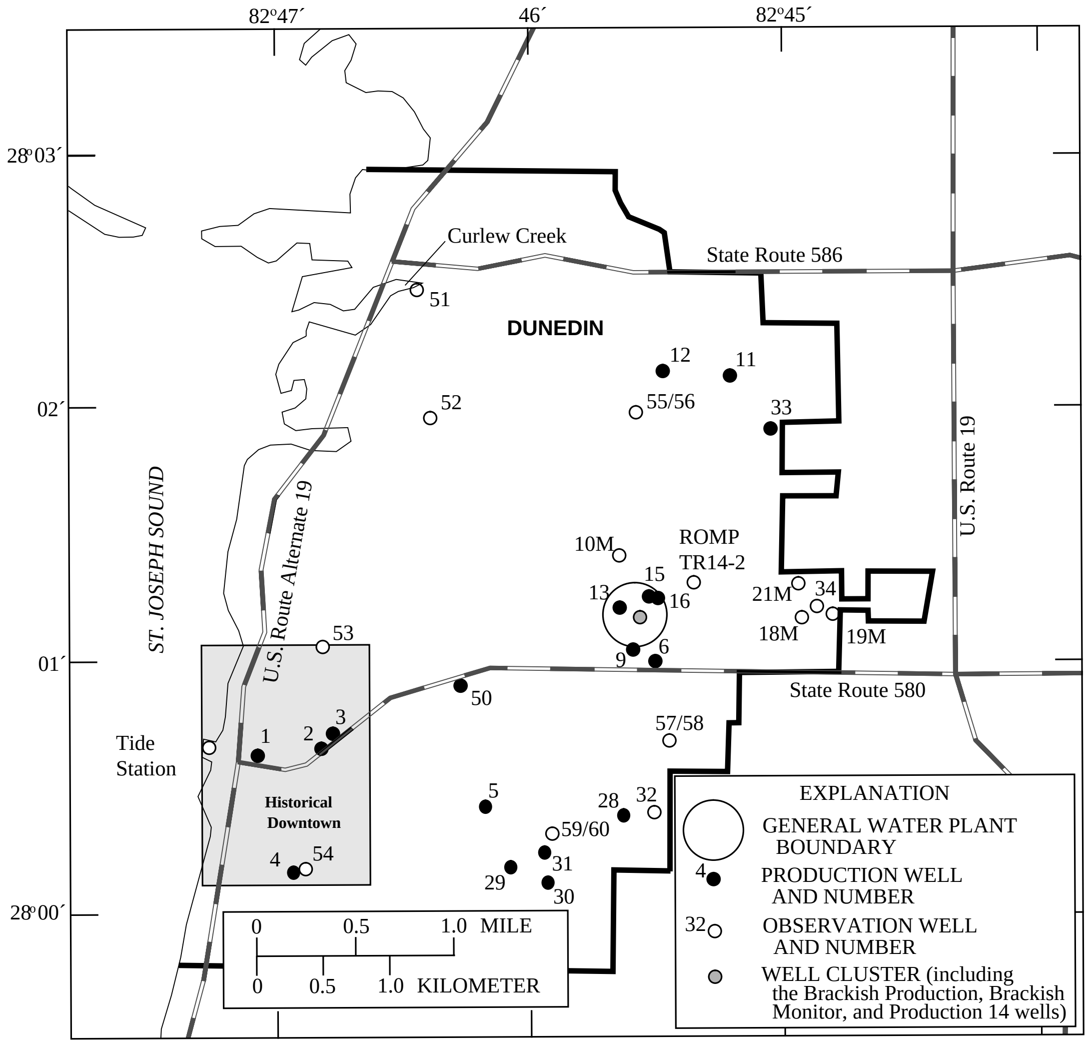
The 156 mi^2 study area includes most of northern Pinellas County and encompasses the Dunedin well field located near the center of the study area (fig. 1a). Pinellas County is a peninsula in west-central Florida situated between the Gulf of Mexico and Tampa Bay. The brackish production and brackish monitor wells, drilled as part of this study, are located at the Dunedin water plant (fig 1b). The area is predominately urban; the population density of Dunedin is approximately 4,750 persons per mi^2.

The study area is part of the Gulf Coastal Lowlands physiographic province comprised of scarps and terraces created during various Pleistocene sea-level stands. Heath and Smith (1954) recognized three of these terraces in the study area. The topographic surface ranges from sea level at the coast to 65 feet (ft) above sea level on the eastern boundary of Dunedin.



Base from Southwest Florida Water Management District digital data, 1:250,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 1a. Location of the study area and selected U.S. Geological Survey network wells. (Location and name.)



Base from Southwest Florida Water Management District digital data, 1:250,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 1b. Location of the existing production wells and observation wells, new wells drilled as part of the study, generalized water plant boundary, and historic downtown district Dunedin, Florida.

Acknowledgments

The author recognizes the invaluable support and cooperation from the city of Dunedin. A special thanks to Steve Rogers, a Dunedin water plant operator and field geologist, for his technical assistance in all data collection and monitoring phases of the investigation. Special thanks also to a dedicated student employee, Rachel Brewer, for her assistance during the aquifer test.

HYDROGEOLOGIC FRAMEWORK AND HYDRAULIC PROPERTIES IN THE STUDY AREA

Water-bearing Cenozoic-age formations in west-central Florida consist of a thick sequence of sedimentary units, deposited during various transgressive and regressive sea-level events, that form a multilayered sequence of higher- and lower-permeability units. The hydrogeologic framework underlying the study area is composed of the surficial and Floridan aquifer systems separated by the intermediate confining unit. The aquifer systems contain one or more permeable zones separated by lower-permeability units (fig. 2). The term semiconfining unit will be used in this report to designate the lower-permeability carbonate units that do not yield large quantities of water to wells. General descriptions of the hydrogeologic units and hydraulic properties were compiled from previous studies. Identification of the permeable zones and semiconfining units within the Upper Floridan aquifer are based on lithologic and geophysical-log data collected as part of this and previous studies. These hydrogeologic units are described in the following sections of the report.

Surficial Aquifer System

In the study area, the surficial aquifer system (SAS) is the uppermost water-bearing unit but it is seldom used for potable water supplies because of its limited thickness (10 to 50 ft). The water table is within 10 ft of land surface and fluctuates less than 5 ft annually. The water table fluctuates seasonally, with lower levels occurring during the dry season (October through May) and higher levels occurring during the wet season (June through September). Recharge to the SAS is from rainfall.

The hydraulic properties of the SAS, in the study area, are highly variable due to the nature of deposition affecting the physical characteristics of grain size, sorting, and thickness. Values of horizontal hydraulic conductivity, vertical hydraulic conductivity, and porosity, reported by previous investigators, range from 13 to 33 feet per day (ft/d) (Cherry and Brown, 1974; Sinclair, 1974), 0.36 to 13 ft/d (Sinclair, 1974; Hutchinson and Stewart, 1978), and 29.2 to 32.2 percent (Hutchinson and Stewart, 1978), respectively.

Intermediate Confining Unit

The low permeability intermediate confining unit (ICU) occurs between the SAS and Upper Floridan aquifer (UFA). The ICU is comprised of interbedded clastics and carbonates that reflect a variety of depositional environments. In the vicinity of Dunedin, the ICU is approximately 60 ft thick and is predominantly composed of clay that retards the vertical movement of ground water between the SAS and UFA.

The hydraulic properties of the ICU are highly variable. The leakance values, reported by previous investigators, range from 0.00001 to 0.015 feet per day per foot ((ft/d)/ft) (Black, Crow, and Eidness, Inc., 1978; Seaburn and Robertson, Inc., 1983; M.P. Brown and Associates, Inc., 1986; Ryder, 1982, 1985). The most plausible values of leakance, in the vicinity of Dunedin, are the values ranging from 0.00001 to 0.0001 (ft/d)/ft reported by Ryder (1982).

Floridan Aquifer System

The Floridan aquifer system is a thick sequence of Tertiary-age limestones, dolomites, and evaporites and includes the UFA, the middle confining unit, and Lower Floridan aquifer (LFA). This report is concerned only with the UFA which includes the following geologic units: the Tampa Member of the Arcadia Formation of the Hawthorn Group, the Suwannee Limestone, the Ocala Group, and the Avon Park Formation (fig. 2). Hickey (1982) subdivided the UFA into four permeable zones separated by semiconfining units. The zones were designated as A, B, C, and D and are used in this report. Only zones A and B contain water that has DS concentrations less than 35,000 mg/L; further discussions will be limited to these permeable zones.

Zone A

In Dunedin, zone A comprises the Tampa Member and the uppermost part of the Suwannee Limestone, and is the shallowest and freshest of the permeable zones. The top of zone A occurs at about sea level and the bottom at about 250 ft below sea level. The values for transmissivity, reported by previous investigators,

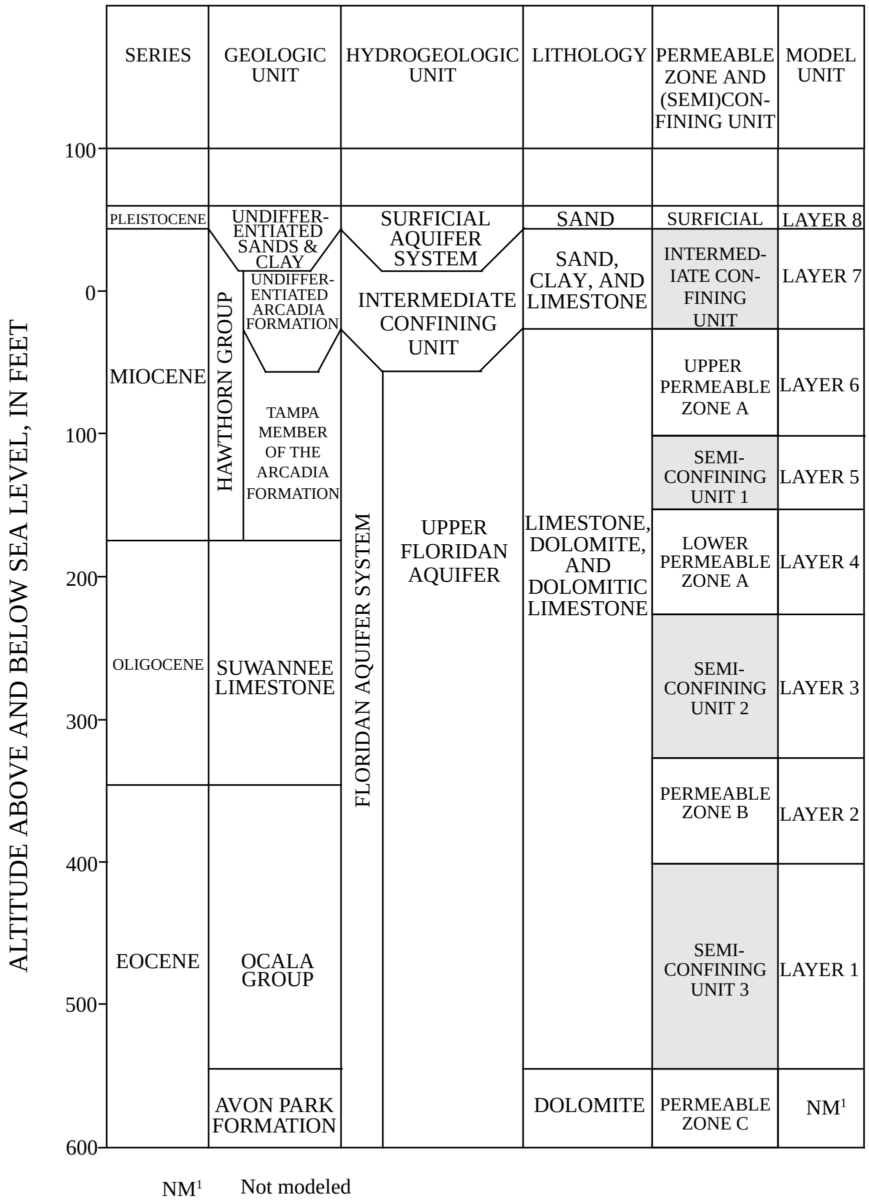


Figure 2. Generalized stratigraphic and hydrogeologic section underlying the study area.

range from 10,000 to 40,000 feet squared per day (ft^2/d) (Hickey, 1982; Seaburn and Robertson, Inc., 1983; and M.P. Brown and Associates, Inc., 1986).

Semiconfining Unit Between Zones A and B

Underlying permeable zone A is the lower Suwannee Limestone that acts as a semiconfining unit (SCU 2). This semiconfining unit averages 80 ft in thickness and is composed of carbonates that do not yield large quantities of water. Cores taken from the semiconfining units, indicate that closed fractures predominate and, therefore, primary porosity rather than secondary porosity controls permeability in the semiconfining units (Hickey, 1982). The published values of vertical hydraulic conductivity of the semiconfining unit range from 0.0013 to 2 ft/d (Hickey, 1982).

Zone B

Permeable zone B is comprised of the lowermost section of the Suwannee Limestone and upper Ocala Group. The unit consists of thin beds of dolomite, dolomitic limestone, and limestone. Zone B averages 60 ft in thickness and is characterized by rapidly changing salinity with depth. Salinity in zone B ranges from 1,500 to 10,000 mg/L DS. Zone B is less transmissive (5,000 ft^2/d) than zones A (10,000 to 40,000 ft^2/d) or C (900,000 to 1,200,000 ft^2/d) (Hickey, 1982, p. 17).

Semiconfining Unit Between Zones B and C

Underlying permeable zone B is the lower Ocala Group that acts as a semiconfining unit (SCU 3). This semiconfining unit averages 140 ft in thickness and is composed of carbonates that do not yield large quantities of water. Cores from this semiconfining unit indicate that the beds have closed fractures; consequently, the unit retards the vertical movement of water between zones B and C (Hickey, 1982, p.18). Calculated vertical hydraulic conductivities range from 0.1 to 1 ft/d (Hickey, 1982, p. 19-20).

Delineation of the Hydrogeologic Units and Producing Zones Underlying the Study Area

Geophysical logs from eight wells were used to further delineate the distribution of zones A, B, and intervening semiconfining units in the study area. These eight wells were selected based on penetration depth and areal distribution. The locations and identification names or numbers of the eight wells are shown in figure 3; well-construction data are listed in the appendix. Three generalized hydrogeologic sections, one oriented north-south, one oriented east-west, and another at the water plant test site were constructed using these eight wells. The distribution of permeable zones and semiconfining units correlated from gamma log traces is shown in figures 4 and 5.

Vertically spaced, discrete water-producing zones are present within zone A (figs. 4 and 5). The vertical position of these producing intervals within zone A is highly variable suggesting that fluid flow occurs through a network of randomly distributed permeable pathways. Generally, the producing zones occur in the upper and lower parts of zone A. These producing zones are separated by semiconfining unit 1 (SCU1). The presence of SCU1 is delineated on gamma logs by a zone of elevated gamma radiation, indicating that interbedded clays exist throughout the study area (fig. 4). Therefore, zone A was partitioned into upper zone A (UZA) and lower zone A (LZA)-- the two being separated by SCU1.

The geologic unit that is the primary source of ground water to wells in the Dunedin well field is the Tampa Member, designated as upper zone A. However, many of the wells penetrate both the upper and lower zone A and some water may be contributed from the producing zone in lower zone A. The average open-hole interval is 162 ft. The term open-hole interval is the depth between the bottom of the casing and the bottom of the well. The wells in the southern part of Dunedin are deeper than those in the downtown area.

Two test wells (the brackish production and brackish monitor wells) were drilled at the Dunedin water plant (fig. 1b) to define the vertical distribution of producing zones. The first test well (the brackish monitor well) was drilled to 550 ft and cased to 60 ft. Interpretations of geophysical logs and packer-test results indicated the existence of three producing zones (fig. 5). The uppermost producing zone, that contributes the majority of water to wells in the Dunedin area, occurs in upper zone A, a second zone occurs in lower zone A, and a third minor producing zone occurs in zone B. The first test well was later cased to 400 ft and back plugged to 465 ft (340-405 ft below sea level). The source of water to the well, following final construction, is zone B.

The second test well (the brackish production well) was drilled to 400 ft and cased to 70 ft. Interpretations of geophysical logs indicated the existence of two

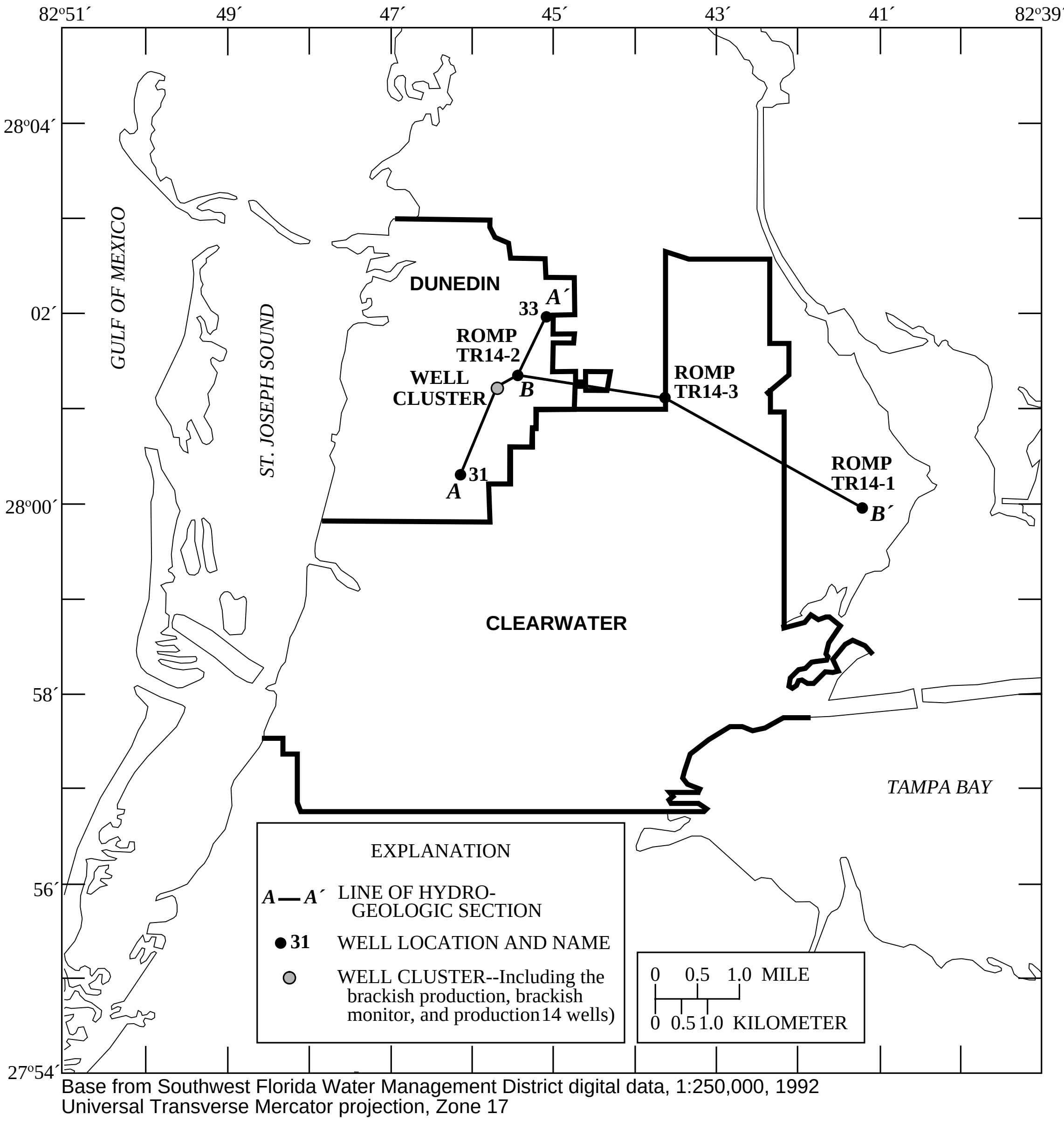


Figure 3. Location of selected wells, well names, and traces of the hydrogeologic sections *A-A′* and *B-B′*.

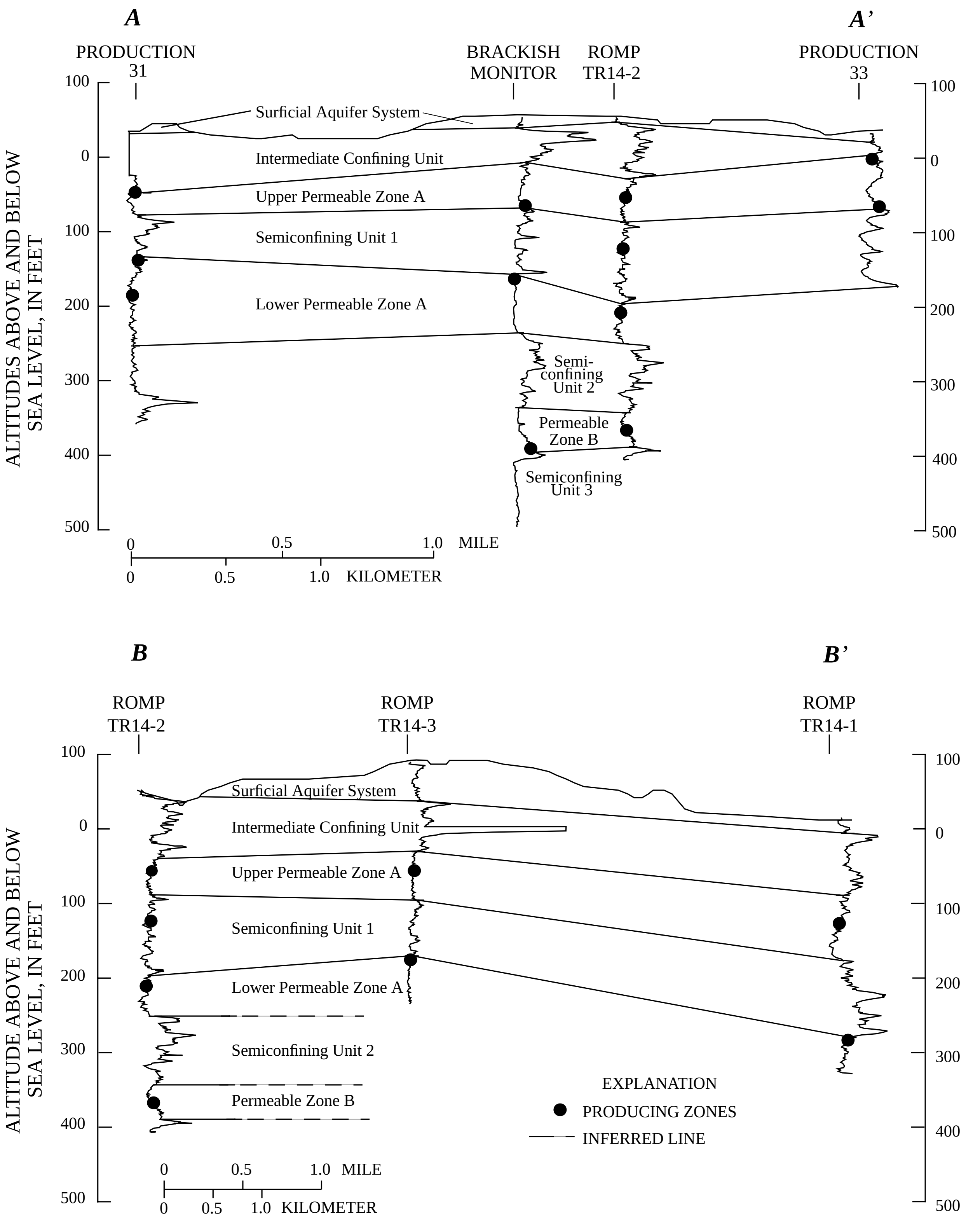


Figure 4. Hydrogeologic sections *A-A′* and *B-B′* showing natural-gamma log traces correlated to permeable zones and semiconfining units.

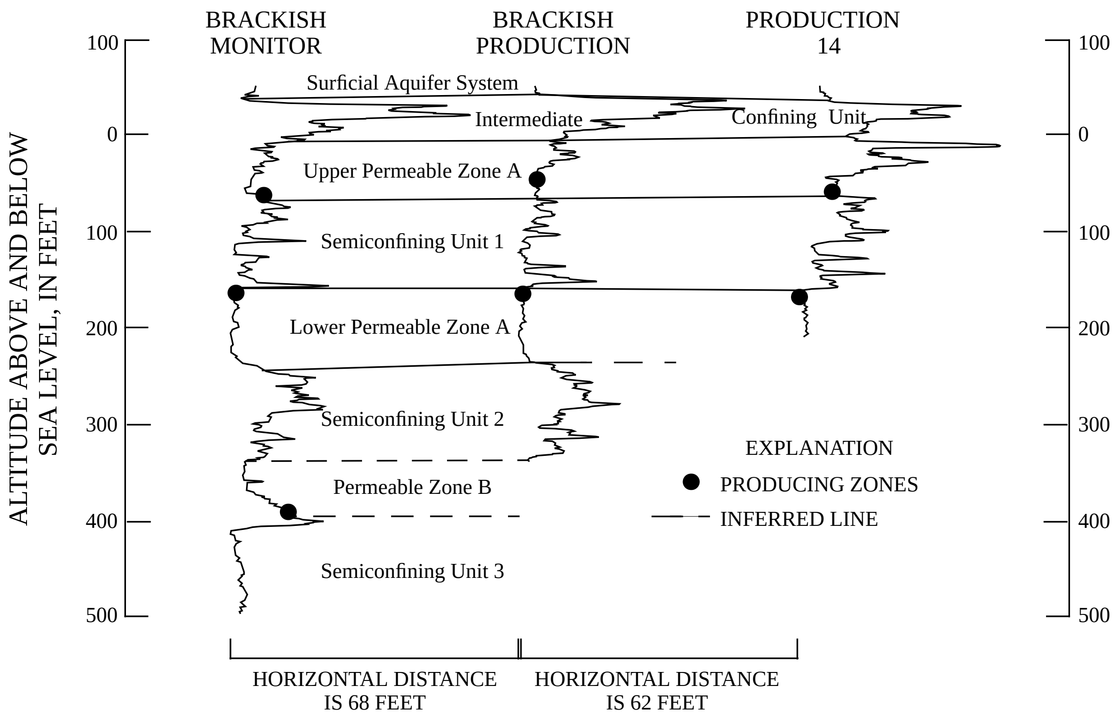


Figure 5. Hydrogeologic units underlying the aquifer-test site showing natural-gamma log traces correlated to permeable zones and semiconfining units.

major producing zones (fig. 5). The uppermost producing zone, that contributes the majority of water to wells in the Dunedin area, occurs in upper zone A and a second zone occurs in lower zone A. The second test well was later cased to 220 ft. The source of water to the well, following final construction, is predominantly from the interval between 220 and 260 ft (160-200 ft below sea level). Additional producing zones were detected from spinner flowmeter measurements at discharge rates of 300, 600, and 1,000 gal/min. As the pumping rate was increased, water to the well was contributed from deeper depths in the borehole.

OCCURRENCE OF GROUND WATER AND GROUND-WATER DEVELOPMENT IN THE STUDY AREA

The occurrence of freshwater in the Upper Floridan aquifer is best characterized as a lens underlain by brackish and saline water. The freshwater portion of the ground-water flow system underlying the city of Dunedin appears to be a local flow system that functions independently of the regional ground-water flow system. A localized flow system is indicated from water-level hydrographs and potentiometric-surface maps.

Water Levels and Dunedin Well-Field Pumpage

Water-level changes resulting from ground-water development have occurred in the study area. Prior to urban development, the primary land use in the study area was for citrus production. The USGS Dunedin 7 1/2-minute quadrangle map for 1943 shows the land use as citrus groves; in 1952, land use was still predominantly citrus groves. Also during this period, well-field pumpage was 10 times greater from the Clearwater well field than from the Dunedin well field (Black and Associates and Bridley, Wild and Associates, Inc., 1952). Hydrographs for Pinellas 665 and Garden Street Triangle wells demonstrate long-term and seasonal water-level patterns (fig. 6). These wells were selected as indicators of water-level response to pumpage in the study area. The hydrographs indicate that water levels decreased during the period 1957-75, stabilized during the period 1975-81, and increased since 1981. Maximum water-level declines in Pinellas 665 and Garden Street Triangle wells, from 1957 -75, were 6 and 4 ft, respectively. Water levels in these wells may be associated with changes in ground-water withdrawals in the study area. Since 1981 the lack of correlation between increases in Dunedin well-field pumpage and increases in water levels in the two observation wells indicates that water-level changes in these wells are probably the result of decreases in ground-water withdrawals in the Clearwater well field and cessation in irrigation pumpage due to increased urban development and loss of citrus groves. These trends indicate that pumpage in the Dunedin well field is probably not affecting water levels in the aquifer outside of Dunedin.

Historical Dunedin well-field withdrawals are shown in figure 7. The construction and production of the wells occurred in stages. Wells 1, 2, 3, 4, 5, 6, and 50 began production in 1958, and well 9 in 1961. Well 11 began production in late 1964, was utilized in 1964, 1965, 1991, and has been in production since 1993. Consequently, well 11 is not shown in figure 7. Well 12 began production in 1965. Wells 13, 14, 15, and 16 began production between 1970-72. Wells 28, 29, and 30 began production in 1985 and were used intermittently until 1988-89. Wells 31 and 33 began production in 1990 and 1992, respectively. The production wells are clustered and are designated as the “downtown wells” (wells 1, 2, 3, and 4), the “water plant wells” (wells 6, 9, 13, 14, 15 and 16), and the “southern area wells” (wells 5, 28, 29, 30, and 31). In addition, three more wells are located in northern Dunedin (wells 11, 12, and 33) (fig. 1b). Current (1994) pumpage from the city of Dunedin is approximately 4.9 Mgal/d. Although total well-field pumpage has increased, withdrawal rates from many of the wells has decreased due to the construction of new wells.

Evaluation of water levels and pumpage records from the water plant wells, supplied by Dunedin personnel for the period 1983-91, indicate that although individual well pumpage has decreased, water levels have not discernibly changed. An example of this relation is shown in figure 8. Production well 14 was selected because it is closest to the centroid of pumping at the water plant and to the test wells drilled as part of this study. Water levels in individual wells generally are not directly affected by changes in individual well pumpage except during 1985 when pumping from production well 14 was significantly reduced (fig. 8).

Ground-Water Flow Patterns

Changes from the historical potentiometric surface do not appear to be substantial, possibly due to the fact that water levels in the study area are controlled by local, rather than regional, conditions. Several investigators, including Heath and Smith (1954, p. 29), have substantiated the occurrence of a local flow system in the study area. Prior to the mapping of the potentiometric surface as part of their 1954 study, it was thought that the water in the Upper Floridan aquifer underlying the study area was derived from recharge in counties to the north (Pasco) and east (Hillsborough) of Pinellas County; however, detailed mapping of the potentiometric surface revealed that in the Dunedin and Clearwater areas of Pinellas County, all of the freshwater recharging the Upper Floridan aquifer is from local precipitation (Heath and Smith, 1954, p.29-31). Freshwater recharge, originating from precipitation, percolates through the hydraulically restrictive intermediate confining unit. Most of the local recharge apparently occurs along the topographic mound near the eastern boundary of Dunedin and Clearwater, where the potentiometric surface is elevated. Rainfall appears to be the only source of freshwater recharge to the Upper Floridan aquifer. Results of another study (Rodney N. Cherry and others, written commun., 1974) indicated the occurrence of the ground-water mound and determined the location of the ground-water divide using flow-net analysis. The analysis indicated that practically no freshwater enters the Pinellas County

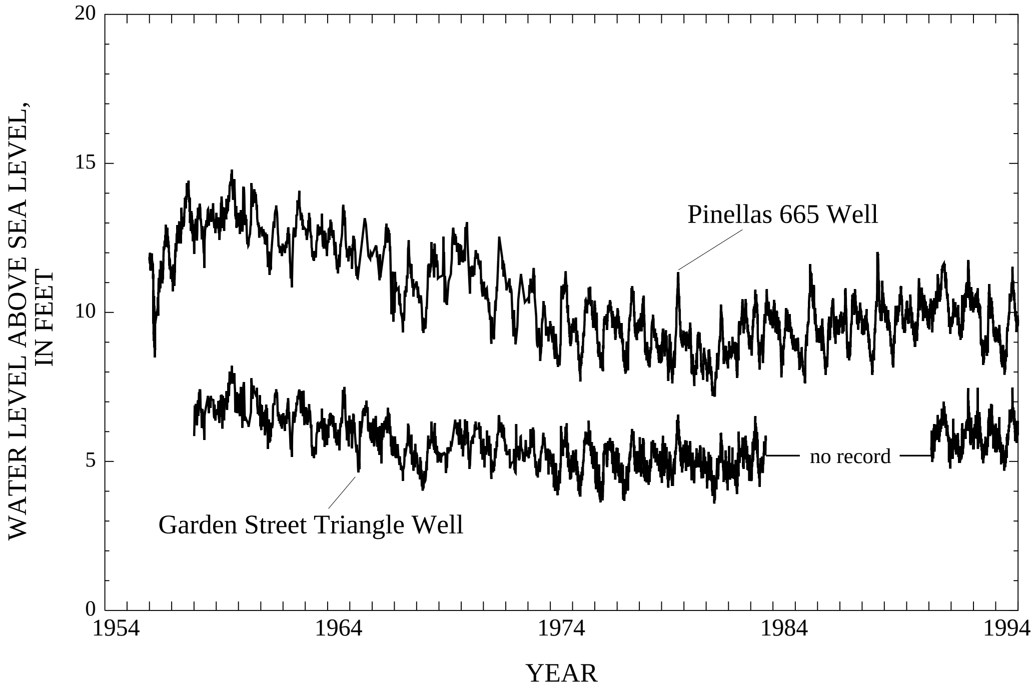


Figure 6. Daily water levels for Pinellas 665 and Garden Street Triangle wells, 1954-94.

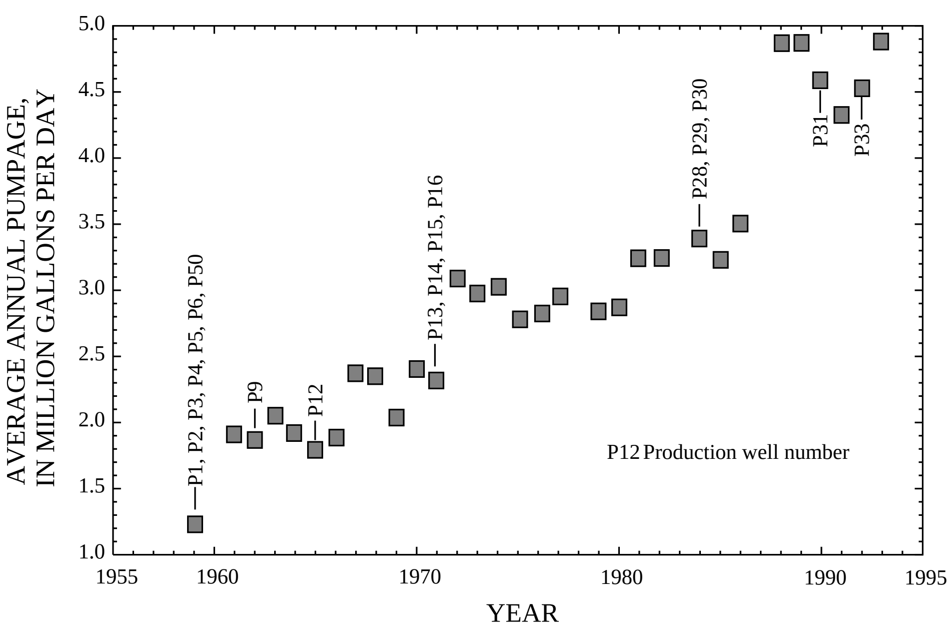


Figure 7. Average annual pumpage and year that production wells went online in the Dunedin well field.

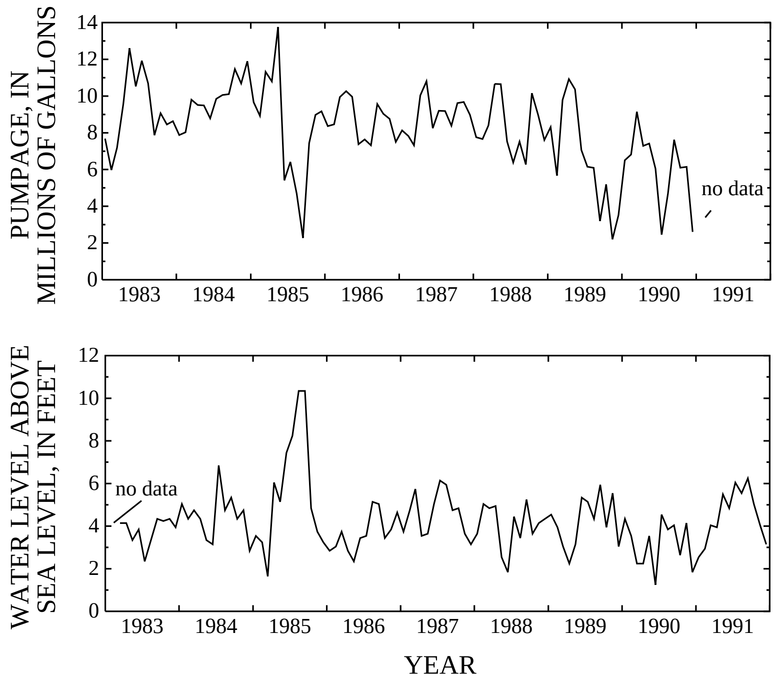


Figure 8. Pumpage and monthly water levels in production well 14, 1983-91.

peninsula as lateral flow in the Floridan aquifer. Hutchinson (1983, p. 19-20) presents two maps showing flow lines drawn on the potentiometric surface of the Upper Floridan aquifer for May and September 1978 in the Tampa Bay area. Both maps show that ground-water flow from the potentiometric-surface high is easterly toward Tampa Bay and westerly toward St. Joseph Sound and the Gulf of Mexico. The depression in the potentiometric surface around Tampa Bay is evidence of the natural discharge of ground water to the bay.

Potentiometric-surface maps were constructed as part of this study. The May and September 1994 potentiometric surfaces of the Upper Floridan aquifer in the study area are shown in figures 9 and 10. Three small, circular depressions in the potentiometric surface are the result of production-well pumpage in the Clearwater and Dunedin well fields. Water levels in eastern Dunedin and Clearwater create a dome-shaped feature on the potentiometric surface. Historically, this potentiometric-surface mound has been a common feature. The mound creates a ground-water divide east of the city of Dunedin indicating that the only source of fresh-water recharge to the Upper Floridan aquifer is local recharge.

GROUND-WATER QUALITY IN DUNEDIN

The Upper Floridan aquifer underlying Dunedin contains a thin lens of fresh-water, maintained by recharge from rainfall, that is underlain by brackish and saline ground water. The spatial water-quality distribution is governed by the fact that ground water underlying Dunedin is a mixture of fresh-water and saltwater that varies both laterally and vertically. This mixture ranges in quality from fresh to saline and has been defined by previous investigators as a transitional type water (Causseaux and Fretwell, 1983). Transitional type waters have chloride concentrations ranging from 25 to 19,000 mg/L. Spatially, the region occupied by this mixture is designated as the transition zone. In general, chloride and DS concentrations increase with depth; however, vertical variations in salinity may occur in the uppermost part of the Upper Floridan aquifer.

Lateral Variations

Average 1993 chloride concentrations in water from wells tapping part or all of zone A were mapped to determine the lateral variations. Chloride concentrations in water from the production wells ranged from 21 to 242 mg/L. Chloride concentrations in water from

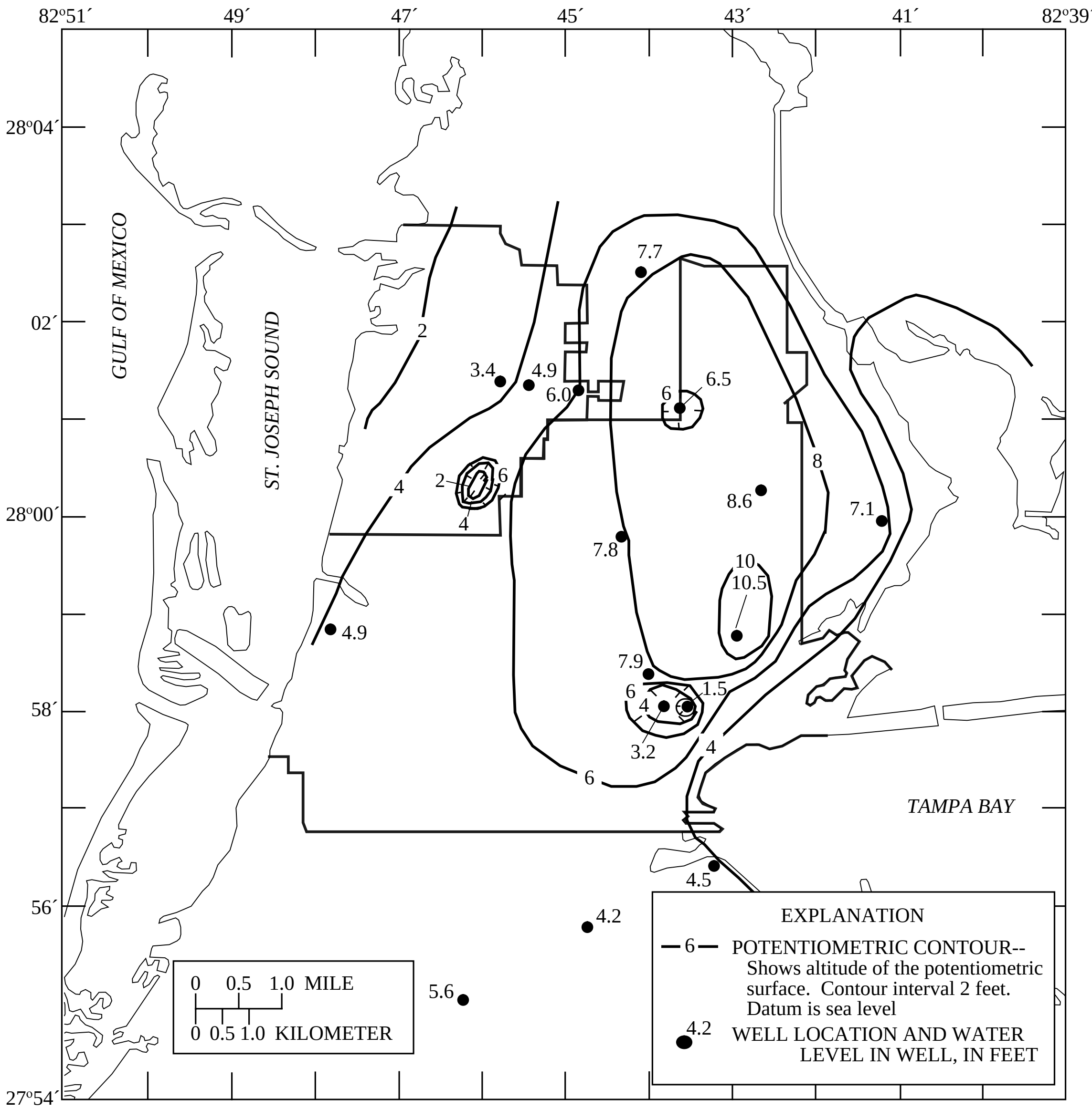


Figure 9. Potentiometric surface of the Upper Floridan aquifer, northern Pinellas County, May 1994.

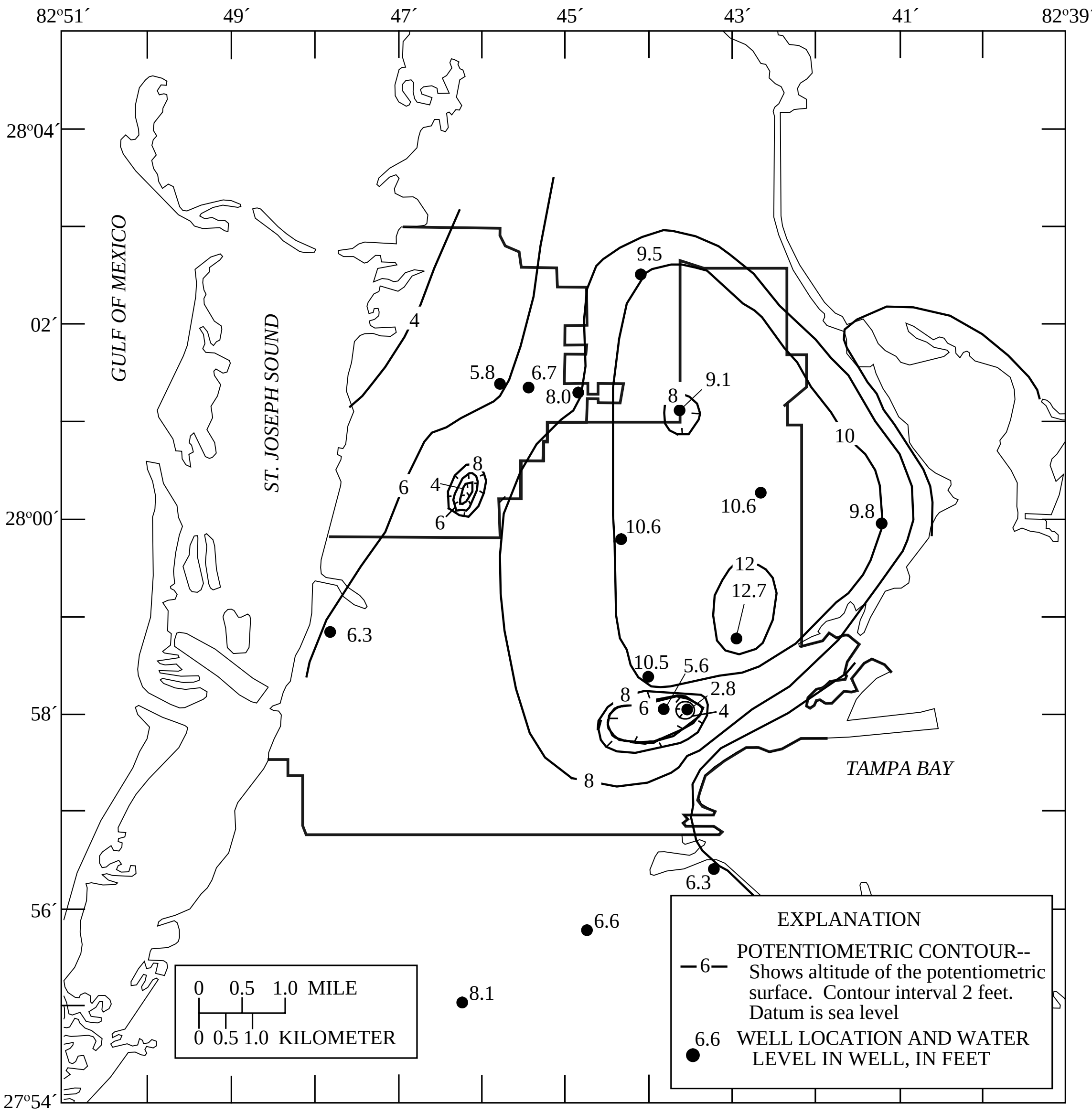


Figure 10. Potentiometric surface of the Upper Floridan aquifer, northern Pinellas County, September 1994.

the observation wells ranged from 35 to 570 mg/L (fig. 11). In general, highest chloride concentrations occur where production wells are clustered rather than in the vicinity of St. Joseph Sound, indicating the source of chloride may be water from deeper zones rather than lateral intrusion of modern seawater. Elevated chloride concentrations occur in some of the observation wells. These observation wells (including 10M, 18M, 19M, and 21M) were originally production wells and it is probable that ground-water withdrawal has had a localized effect on the water quality in these wells. The highest chloride concentration (570 mg/L) was in water from observation well 51. Well 51 is located near the coast and near Curlew Creek. Curlew Creek has incised the limestone of the Upper Floridan aquifer. This breach in the intermediate confining unit may allow direct movement of saline water from St. Joseph Sound into the aquifer; however, statistical analysis indicates that chloride concentrations in water from well 51 have been decreasing at an average rate of 69 mg/L per year for the last 10 years (Dann K. Yobbi, written commun., 1996). This trend does not tend to support lateral movement of modern seawater into the freshwater zones of the Upper Floridan aquifer.

In general, chloride concentrations are highest where pumping is concentrated; however, the chloride concentrations in water from adjacent wells commonly are different even though the wells are similarly constructed. The reasons for this may include: (1) wells penetrate flow zones with different chloride concentrations; (2) the hydraulic gradient between flow zones changes with time affecting the relative contribution from discrete flow zones with differing water quality; and (3) changes with time in water quality of individual flow zones. The chloride concentration in water from each well represents a mixture of water from all producing zones penetrated by the well.

Vertical Variations

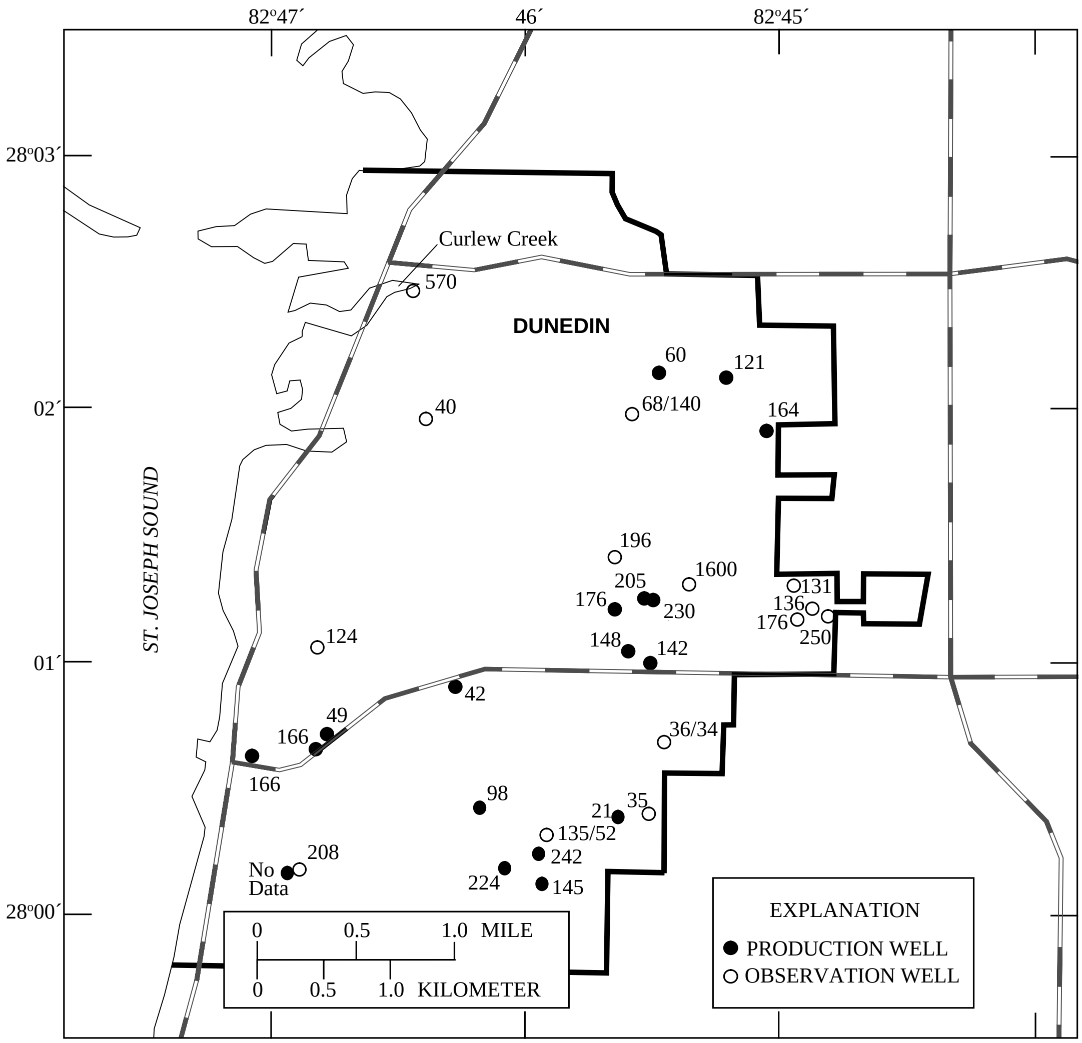
Delineation of the vertical water-quality changes in the uppermost part of the Upper Floridan aquifer was accomplished by evaluating the distribution of selected chemical constituents from water samples collected during well construction and packer testing.

Values of specific conductance were plotted to show the vertical variations within the Upper Floridan aquifer (fig. 12). The data show that water with elevated specific conductance occurs in both upper and lower zone A and water with lower specific conductance occurs in semiconfining unit 2. Water from wells that penetrate zone B show a dramatic increase in specific conductance in this zone. Data from the brackish monitor and TR14-2 wells indicate that saline water occurs deeper than 400 ft below sea level.

As part of this study, water-quality samples were collected at selected intervals from both the brackish monitor and brackish production wells to characterize the vertical distribution of chemical constituents in water from discrete producing zones. Water samples were collected after the test wells were drilled using a thief sampler, a Fultz pump with a 1/4-inch drop pipe, and a submersible pump during packer testing. The depth intervals sampled correspond to locations of producing zones indicated by geophysical logs and spinner flowmeter measurements.

Stiff diagrams showing major ion concentrations of water samples from selected depths in the brackish monitor well illustrate the vertical distribution of water types and salinity in the Upper Floridan aquifer (fig. 13). The shape of the diagram indicates the water type; for example, a “T” shape indicates sodium chloride type water and a “diamond” shape indicates a calcium bicarbonate type water. The size of the diagram indicates concentration (the larger the diagram the higher the DS). Stiff diagrams for water from the brackish monitor well indicate a sodium chloride type water throughout the interval sampled. These “T” shaped stiff diagrams and the trend of increasing size (concentration) with depth are likely the result of upward flow of higher salinity water from zone B, rather than natural conditions within zone A. The stiff diagrams for water samples collected from the brackish production well are somewhat anomalous. Above a depth of 334 ft below sea level, the water is a sodium chloride type; however, the size (concentration) decreases with depth. The sodium and chloride concentrations decrease throughout the interval between 286 and 334 ft below sea level. A calcium bicarbonate type water was present at the bottom of the well. This trend also was supported by interpretation of the fluid resistivity log.

The layering of higher salinity water over lower salinity water in the uppermost Upper Floridan aquifer, as observed in wells in the vicinity of Dunedin (figs. 12 and 13), could result from: (1) past seawater encroachment into zones of higher permeability during the higher Pleistocene sea-level stands and incomplete flushing of the seawater by the present-day flow system; or (2) the occurrence of structural features, such as



Base from Southwest Florida Water Management District digital data, 1:250,000, 1992
Universal Transverse Mercator projection, Zone 17

Figure 11. Chloride concentrations, in milligrams per liter, in selected wells penetrating zone A, 1993, Dunedin, Florida. (Wells are identified in figure 1b.)

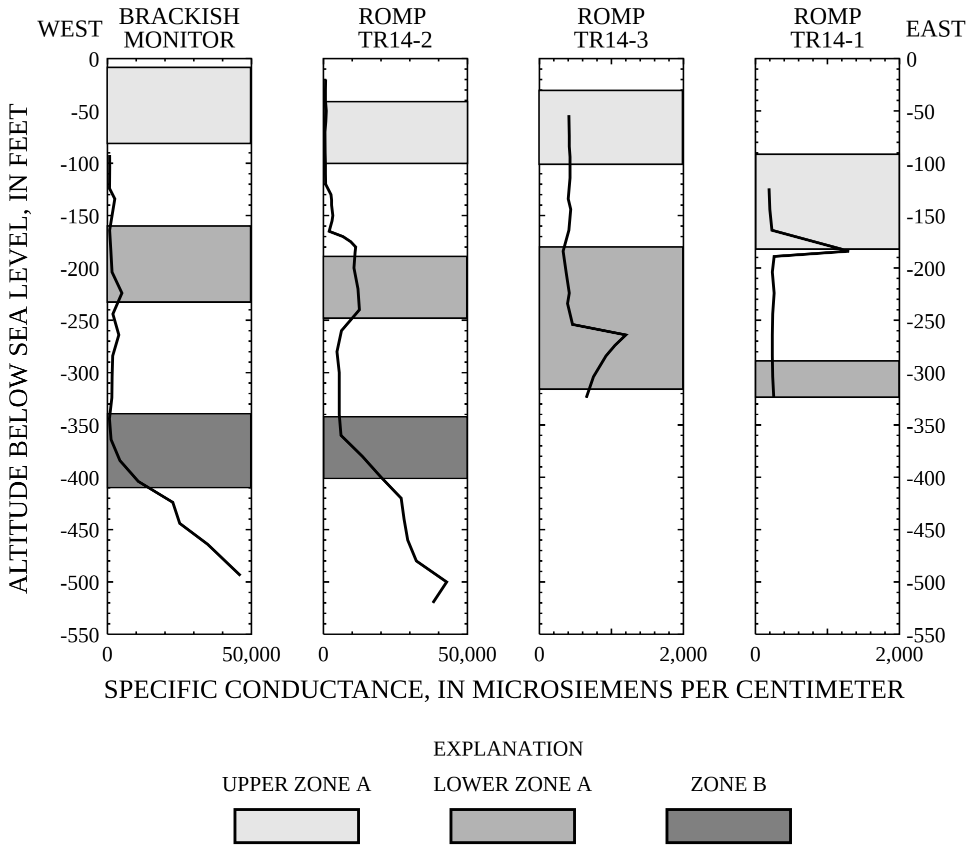


Figure 12. Specific-conductance profile during well drilling.

fractures, that provide hydraulic connection to sources of saline water. Available data indicate that the relatively shallow zones of higher salinity correspond to zones of relatively higher transmissivity in the Upper Floridan aquifer. Deeper in the Upper Floridan aquifer (within and below zone B), the water changes rapidly from fresh to saline.

Temporal Variations

To understand the dynamic changes in the flow system, temporal variations in water quality, as indicated by chloride, were evaluated. Chloride-concentration data from the Dunedin production wells have been tabulated since 1970. As part of another USGS study, water-quality data were statistically analyzed for trends (Dann K.Yobbi, written commun., 1996). Table 1 presents the statistical trend-analysis of chloride concentration in the production and observation wells in Dunedin. In general, the quality of water from production wells has changed between 1970-95. Increasing chloride-concentration trends are occurring in water from all production wells except production well 4. Statistical trend-analysis of data from the past 10 years indicates that chemical changes also are occurring at production well 4. The rate of change in chloride concentration is not uniform throughout the well field (table 1); however, the greatest rate of change at most of the wells has occurred since 1988. Long-term chloride concentrations for the six water plant production wells are shown in figure 14. Combined pumpage from these six wells increased from 1 Mgal/d in 1970 to 1.9 Mgal/d in 1980 and then decreased to 1.05 Mgal/d in 1990. Total well-field pumpage increased from 2.4 Mgal/d in 1970 to 4.9 Mgal/d in 1994. Although total well-field pumpage has increased, individual well pumpage has decreased; however, decreases in individual production-well withdrawal have not altered the chloride-concentration trend.

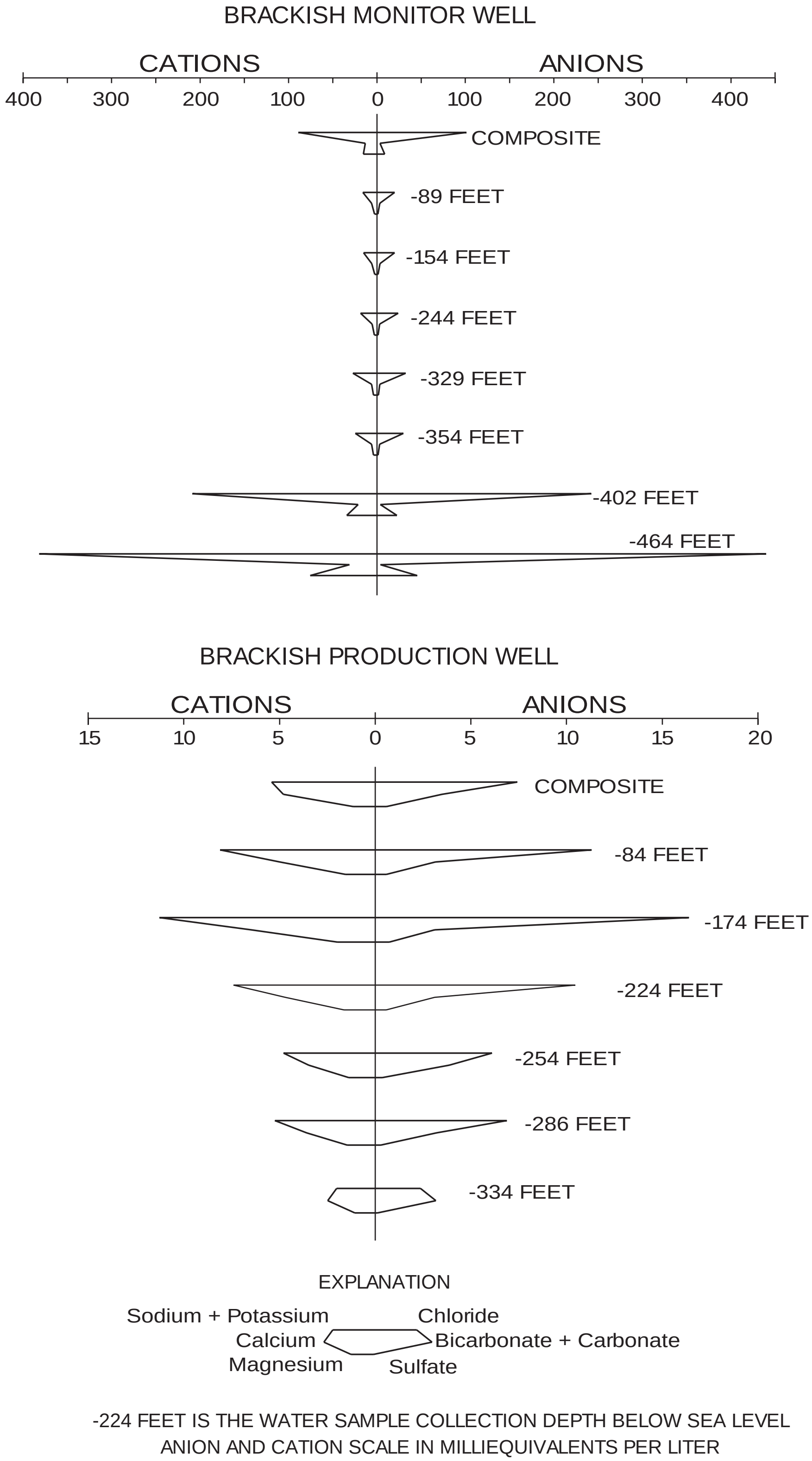


Figure 13. Stiff diagrams of major ions from selected depths in the brackish monitor and brackish production wells.

Table 1. Records of the city of Dunedin production and observation wells and trend analysis results of chloride concentration

[n, sample size; ρ, significance level (positive value indicates increasing trend, negative value indicates decreasing trend); HS, highly significant (ρ ≤ 0.01); S, significant (0.01< ρ ≤ 0.05); MS, marginally significant (0.05 < ρ ≤ 0.10); *, not significant (ρ > 0.10); mg/L, milligrams per liter; ND, means less than 10 years of data available; same, means same data set for all available data and 1985-94 water years]

Well name or number	Station number	All available data				Data for 1985-1994 water years		
		Period of record	n	ρ	Trend (mg/L)	n	ρ	Trend (mg/L)
1	2800450824722	1970-95	848	HS	2.3	515	*	*
2	2800460824709	1970-95	936	HS	4.0	610	*	*
3	2800490824704	1970-95	942	HS	0.8	600	HS	1.7
4	2800120824715	1970-92	639	*	*	314	HS	5.9
5	2800320824625	1970-95	849	HS	2.0	516	HS	8.4
6	2801120824537	1971-95	887	HS	2.7	567	HS	6.2
9	2801140824543	1970-95	913	HS	2.0	576	HS	6.3
10M	2801390824548	1970-95	484	S	3.6	147	*	*
11	2802290824513	1987-95	137	S	18.7	ND	ND	ND
12	2802290824534	1970-95	852	HS	0.8	511	HS	1.6
13	2801230824546	1971-95	923	HS	3.3	592	HS	6.3
14	2801230824541	1970-92	685	HS	2.2	356	*	*
15	2801250824540	1971-95	833	S	1.9	521	HS	7.6
16	2801250824531	1971-95	865	HS	4.8	552	HS	8.3
18M	2801230824459	1977-95	450	S	5.6	210	*	*
19M	2801240824449	1978-95	498	HS	14.5	258	HS	19.6
21M	2801320824500	1977-95	426	*	*	182	*	*
28	2800280824545	1985-95	344	HS	12.7	same	same	same
29	28000110824621	1985-95	410	HS	20.5	same	same	same
30	2800100824610	1985-95	404	HS	16.5	same	same	same
31	2800190824606	1985-94	178	HS	30.3	ND	ND	ND
33	2802150824510	1991-94	63	*	*	ND	ND	ND
34	2801260824455	1992-95	39	*	*	ND	ND	ND
50	2801020824632	1987-95	87	*	*	ND	ND	ND
51	2802490824643	1992-95	38	MS	-69.4	ND	ND	ND
52	2802150824639	1992-95	40	*	*	ND	ND	ND
53	2801140824707	1992-95	40	MS	-6.1	ND	ND	ND
54	2800150824711	1992-95	40	MS	-43.6	ND	ND	ND
55	2802170824544	1992-95	39	*	*	ND	ND	ND
56	2802170824544	1992-95	37	MS	3.0	ND	ND	ND
57	2800500824534	1992-95	37	S	2.5	ND	ND	ND
58	2800500824534	1992-95	34	S	3.2	ND	ND	ND
59	2800200824607	1992-95	38	*	*	ND	ND	ND
60	2800200824607	1992-95	35	*	*	ND	ND	ND

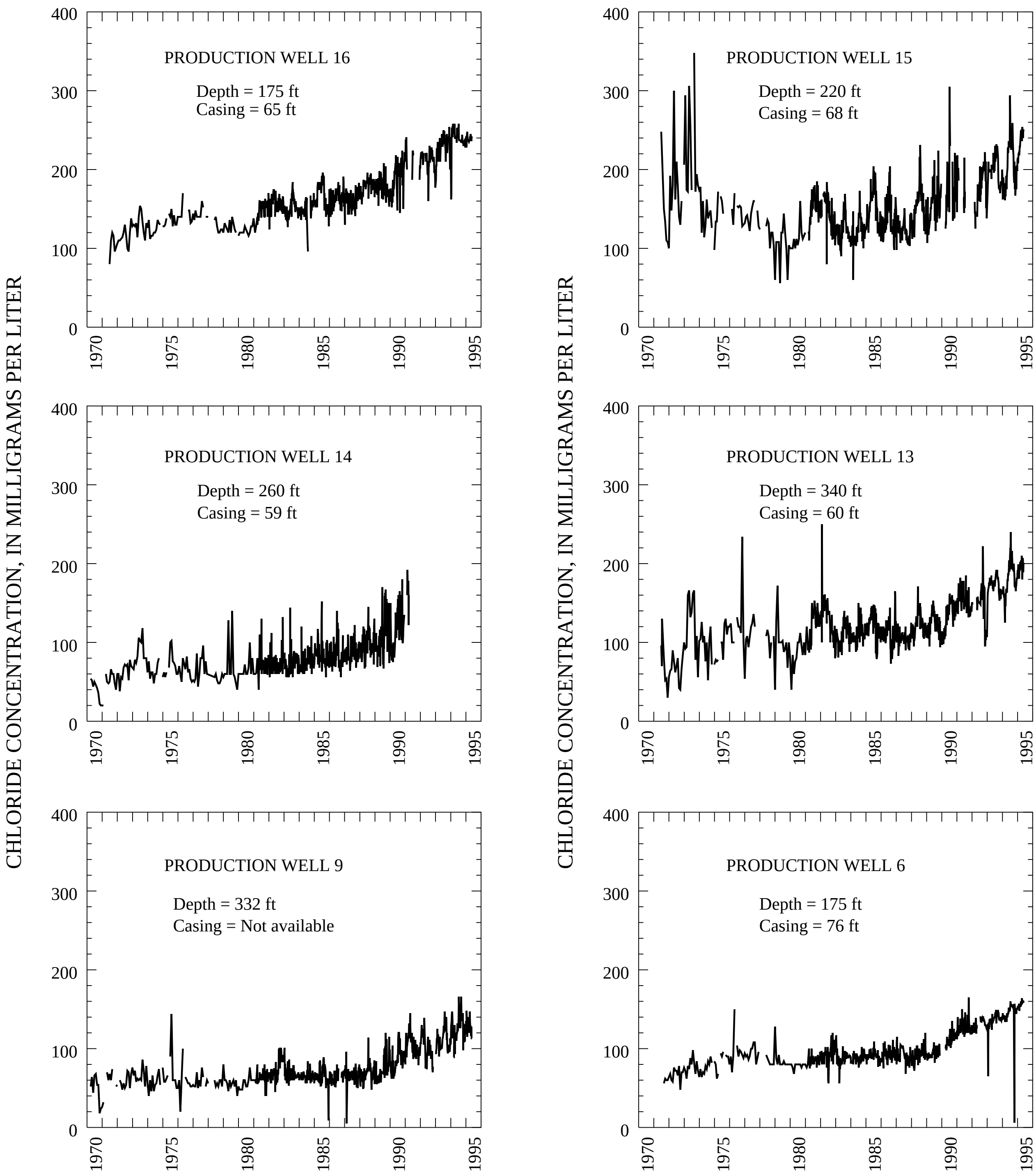


Figure 14. Chloride concentrations in water from production wells 16, 15, 14, 13, 9, and 6, 1970-94.

The localized effect of pumping on chloride concentration in water from the Dunedin observation wells is indicated by the results of the statistical trend analysis (table 1). The annual changes in chloride concentration range from -69.4 to 14.5 mg/L per year. Wells with decreasing chloride-concentration trends occur near the coast (wells 51, 53, and 54); one possible reason for this trend is the cessation of irrigation pumping from nearby wells in the Dunedin Country Club. Wells with increasing chloride-concentration trends were originally production or irrigation wells (wells 10M, 18M, 19M, 55/56, 57/58, and 59/60). Ground-water withdrawal has likely had a local effect on water quality from these wells.

The observed increasing chloride-concentration trend in water from Dunedin production wells is probably the result of three factors. The most important factor is the relation between the position of water-producing zones in the well and increasing chloride concentration with depth in the aquifer; wells receiving water from deeper producing zones may allow direct pumping of water with elevated chloride concentrations. A second factor is the upward movement of water with elevated chloride concentrations caused by well pumpage. A third factor is lateral movement of water with elevated chloride concentrations. This factor is less important because lateral chloride-concentration changes occur over a distance of miles, whereas vertical changes occur over a distance of hundreds of ft.

BRACKISH PRODUCTION-WELL AQUIFER TEST

Aquifer testing is a method for quantifying hydraulic properties of aquifers. Typically, a well is pumped at a constant rate and the drawdown and recovery of water levels in one or more observation wells are measured. The drawdown and recovery data are analyzed using analytical equations and various type-curve matching techniques. A 3-day aquifer test was conducted as part of this study.

Background Data

Water levels were measured continuously at the following wells: brackish production, brackish monitor, production 14, ROMP TR14-2 Tampa and Ocala, 18M, 10M, and 57. Tide stage of the Gulf of Mexico was measured continuously at the Dunedin Marina. Data were collected for about a year and spanned the period of 5 months prior to and 7 months after the aquifer test. The data were collected using electronic water-level monitoring equipment including Campbell Basic Data Recorders (BDR 301), Design Analysis pressure transducers, or Handar shaft encoders with float/weight water-level-measurement devices.

Hydrographs were constructed to better understand the water-level response in a multilayered aquifer. Examples of the hydrograph data for the period April 5-26, 1995, are shown in figure 15. The hydrographs indicate that water levels in wells are tidally affected. In addition, water levels in some of the observation wells (10M and production 14) are affected by all pumping rate changes within the Dunedin well field. Water levels in other wells (18M and 57) are affected by maximum pumping rates corresponding to permitted watering days. Water levels in some wells (TR14-2 Ocala and Tampa and brackish monitor) do not appear to be affected by well-field pumpage. This variability in water-level response to well-field pumpage indicates that the Upper Floridan aquifer is a multilayered system. The average seasonal fluctuation is about 2 ft and ranges from 1 to 3 ft.

Differences in water levels among the wells indicate that head increases with depth, indicating that in the Upper Floridan aquifer the ground-water flow potential is upward. An apparent exception to this trend is the ROMP TR14-2 Ocala well. After the water levels were corrected for salinity, the equivalent freshwater head was 8.77 ft higher than the measured head. After the salinity corrections were made, it was apparent that water levels throughout the Upper Floridan aquifer increase with depth, and the upward head gradient likely is the dominant mechanism for chloride-concentration changes.

Aquifer-Test Design and Implementation

The USGS conducted an aquifer test at the study site in August 1994. As pumping commenced at the brackish production well, water levels were measured in seven observation wells, including the brackish monitor, production 14, ROMP TR14-2 Tampa, ROMP TR14-2 Ocala, 18M, 10M, and 57. The purpose of the test was to determine the hydraulic properties of upper and lower zone A, zone B, and the intervening semiconfining units (SCU1 and SCU2). The pumped well and the observation wells penetrate to varying degrees, upper and lower zone A, zone B, and the semiconfining units. Well construction information is listed in the appendix. Water levels were measured at the pumped well and seven observation wells.

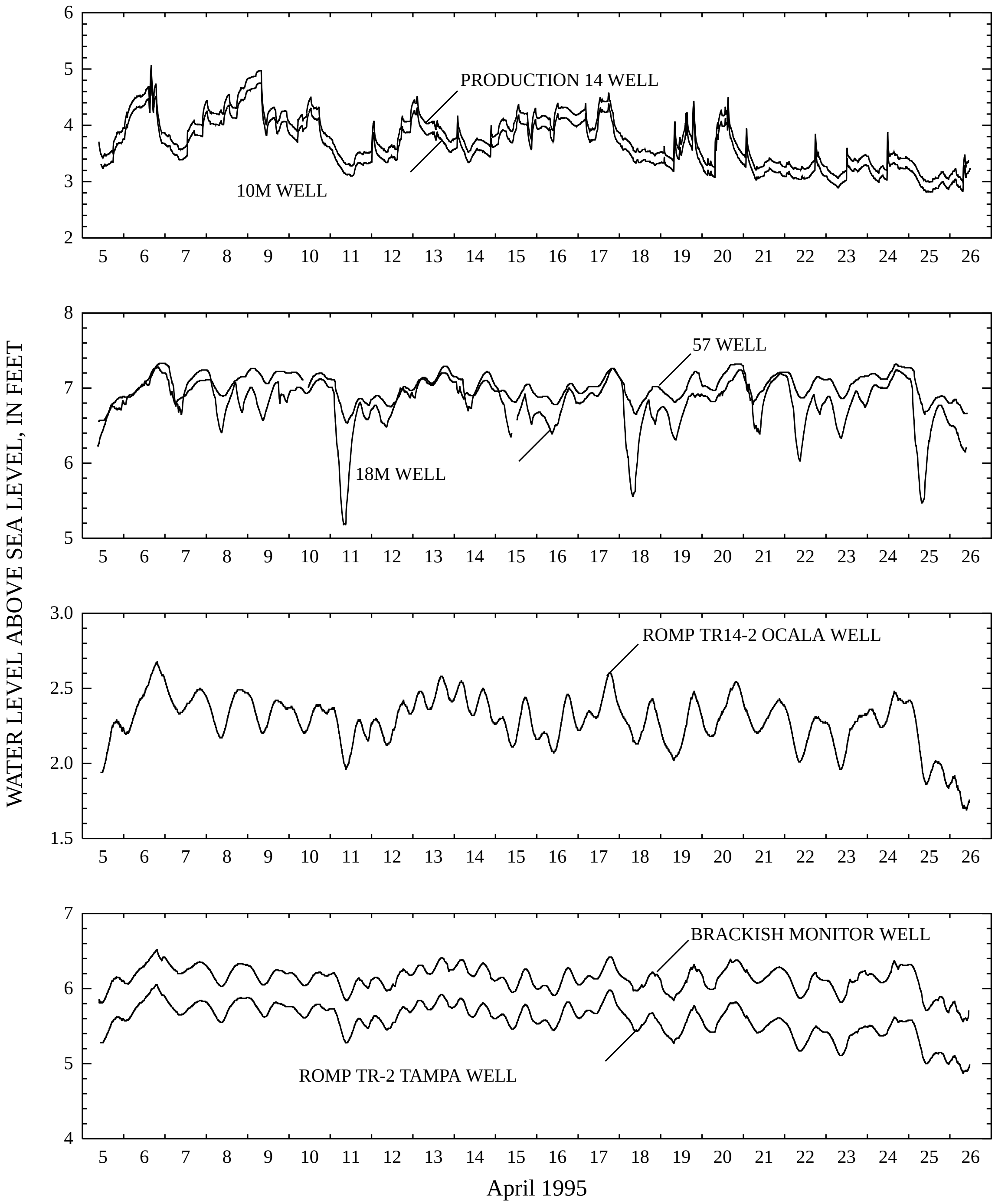


Figure 15. Water levels from observation wells illustrating aquifer response in a multilayered aquifer system, April 5-26, 1995. (Note that the production well 14 is consistently higher than the 10M well. The 57 well is consistently higher than the 18M well.)

The test began at 0910 hours on August 16, 1994, with an average pumping rate of 670 gal/min; unfortunately, the pump stopped at 2330 hours on August 16, 1994. The test was restarted at 0200 hours on August 17, 1994, with an average pumping rate of 690 gal/min. The test ended at 0910 hours on August 19, 1994.

Water levels in three of the seven observation wells exhibited a noticeable response to pumping the brackish production well. Because water levels in 10M and production 14 behave identically, only data for the brackish monitor and production 14 wells were analyzed. The data were corrected for tidal effects. The calculated tidal efficiency is 7 percent. The tidal efficiency may be calculated and drawdown data may be adjusted for tide-stage changes occurring during an aquifer test by measuring stage fluctuations prior to and during the test and applying the equation presented by Ferris and others (1962).

The tidally corrected drawdown data are shown in figure 16. Additional drawdown measured in production 14, 200 minutes into the test, is believed to have resulted from increased pumpage from the nearby production wells. Attempts were made to analytically analyze the test; the results are discussed in the following section of the report.

Limitations of Analytical Aquifer-Test Analyses

Conducting careful, controlled, and successful aquifer tests of the hydrogeologic units of the Upper Floridan aquifer is difficult because the aquifer has a layered and non-uniform permeability distribution. In addition, characterizing hydraulic properties is more difficult in heterogeneous, fractured rock than in homogeneous, granular rock. At small scales, on the order of inches (in) to ft, significant variations in hydraulic conductivity arise from the presence or absence of fractures. At larger scales, on the order of tens to hundreds of ft, variations in hydraulic conductivity arise from the presence of zones of numerous, open well-connected fractures versus sparse, tight, poorly connected fractures. Consequently, hydraulic properties quantitatively determined at a particular location in the aquifer may not be representative of properties at an adjacent location (Paul A. Hsieh, written commun., 1992).

Several analytical models were utilized in an attempt to quantify the hydraulic properties of the permeable zones and semiconfining units. Results of the analyses were highly variable and precluded the determination of reliable hydraulic properties of the hydrogeologic units underlying the Dunedin well field.

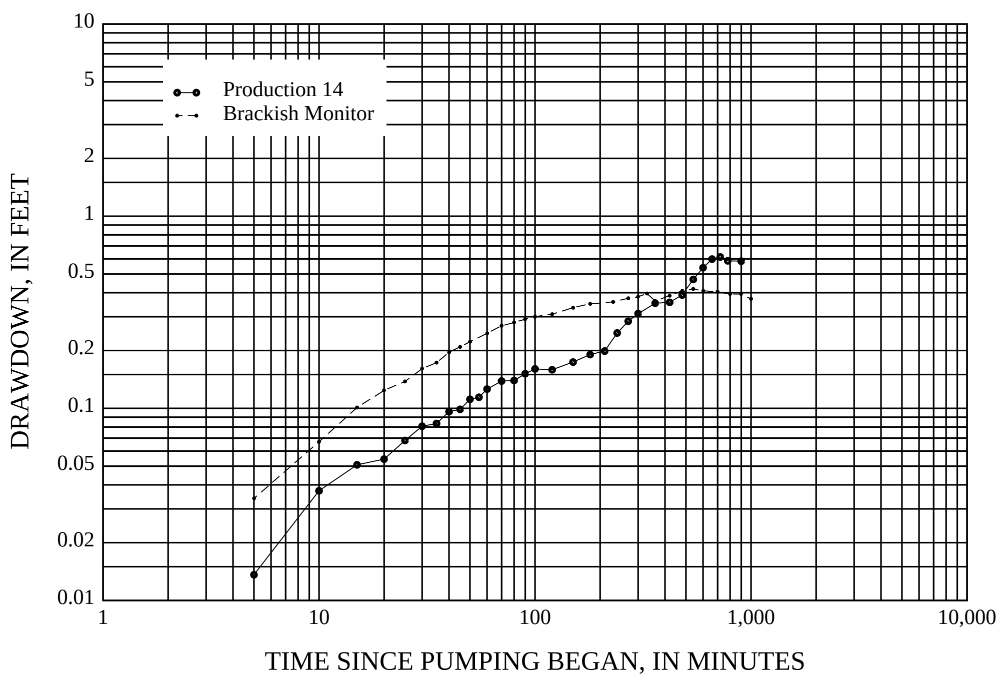


Figure 16. Aquifer-test data from the brackish monitor and production 14 observation wells.

Possible reasons for why the analytical models failed include the less than optimal distribution of observation wells, pumping interference, and the heterogeneous nature of the multilayered Upper Floridan aquifer.

The drawdown data were provided at the request of the cooperator (city of Dunedin) to their consultant Leggette, Brashears, and Graham. Results of aquifer-test analysis by Leggette, Brashears, and Graham (1995), using the USGS water-level data, were also highly variable. Calculated transmissivity values ranged over three orders of magnitude (6,000 to 240,000 ft^2/d) using various analytical methods. Storativity values were greater than 1 for five of the 10 analyses. The final conclusion of the consultant's report (1995) is that the calculation of aquifer properties in the study area when using simple analytical equations is ambiguous.

An alternative approach to analytical analysis of aquifer-test data is numerical analysis. Hutchinson and Trommer (1991) showed that, in contrast to analytical approaches, numerical analysis was not constrained by multiple phases of discharge and recovery, length of testing, assumptions concerning storage within a semiconfining unit, or number of layers in the hydrogeologic system. The 3-day aquifer test was analyzed using the Heat and Solute Transport in Three-Dimensions (HST3D) numerical code to derive hydraulic properties of the multilayered aquifer underlying Dunedin and is discussed in the following sections of the report.

NUMERICAL SIMULATION OF THE FRESH- AND BRACKISH-WATER RESOURCES UNDERLYING DUNEDIN

A digital modeling approach was used to simulate density-dependent, ground-water flow and advective-dispersive transport of a conservative ground-water solute (chloride ion) using geologic, hydrologic, and chemical data collected as part of this study. Two of the tasks of this study were to derive hydraulic properties of the multilayered aquifer underlying Dunedin and to estimate changes in water quality in response to development of the brackish ground-water resources.
A cylindrical ground-water flow and solute-transport model was developed to test and refine the conceptualization of the hydrogeologic system underlying Dunedin. The model was utilized as an interpretative tool in which simulated water levels and water quality could be tested against observed water levels and water quality to derive reasonable estimates of the hydraulic properties of and water-quality distribution in the uppermost Upper Floridan aquifer. Numerical simulation was a two-phase process. The initial phase was to simulate the 3-day aquifer test; the second phase was to simulate long-term water-quality changes.

The following sections of the report include descriptions of the numerical methods, the conceptual model, and the selection of parametric coefficients to represent aquifer characteristics based on data acquired at the brackish well test site. Determination of the hydraulic characteristics was accomplished by replicating field data acquired during the aquifer test at the Dunedin water plant. Determination of the chemical characteristics was accomplished by replicating chloride-concentration changes in water from the six water plant wells over a 25-year period (1970-94). Estimates of chloride-concentration changes resulting from the addition of brackish ground-water development were made.

Numerical Methods

The USGS computer code HST3D (Kipp, 1987), which solves the equations for ground-water flow and solute transport using a finite-difference approximation, was used. HST3D was the selected simulator because it can simulate variable-density ground-water flow. Backward-in-time and backward-in-space finite-difference equations were used to solve the ground-water flow and solute-transport equations in the simulator code. The reader is referred to Kipp (1987) for a discussion of the numerical methods used in the simulator code.

Conceptual Model

The hydrogeologic system underlying Dunedin is conceptualized as containing multiple permeable zones separated by leaky semiconfining units. Ground-water quality changes from fresh to saline with depth. Eight layers were delineated to represent the hydrogeologic framework underlying Dunedin. These eight layers include the portion of the aquifer containing water with less than 35,000 mg/L DS and correspond to the 20-ft thick surficial aquifer system (layer 8), the 60-ft thick intermediate confining unit (layer 7), the 80-ft thick upper zone A (layer 6), the 60-ft thick semiconfining unit 1 (layer 5), the 80-ft thick lower zone A (layer 4), the 100-ft thick semiconfining unit 2 (layer 3), the 60-ft thick zone B (layer 2), and the 140-ft thick semiconfining unit 3 (layer 1) (fig. 17). Evidence from geophysical logs and water-level and water-quality differences support this conceptualization and zonation of the multilayered, variable density aquifer underlying Dunedin.

Due to the complexity of the hydrogeologic system, lack of consistent pressure (water level/head) and concentration (chloride) data, and multiple stresses (tidal and pumping) on the ground-water flow field, a numerical model with cylindrically symmetric coordinates was constructed to emphasize the vertical features of the system. Characteristically, chloride concentrations will have a greater rate of change in the vertical direction than in the lateral direction. It is often advantageous to use simplified models to conceptualize the hydrologic system and to assess uncertainty associated with aquifer properties. The model represents a 600-ft thick section underlying the Dunedin water plant, because this site is the test site for the first brackish-water well and relatively more data exist for this region.

The conceptual model incorporates several major assumptions about the hydrogeologic framework and, therefore, only approximates the actual aquifer. One of the major assumptions is that the aquifer behaves as an equivalent porous medium; however, field data indicate that the aquifer may be highly heterogeneous and anisotropic due to fracturing and dissolution of the carbonate rocks. Compounding this problem is the unavailability of data for some of the hydrogeologic units and inconsistency of data within hydrogeologic units. Therefore, imprecise estimations of parameter values are likely during the process of matching simulated to observed data.

Spatial Discretization

The test site was simulated using a cylindrical-coordinate grid of 97 columns and 30 rows. The spatial discretization consists of 97 variably spaced vertical columns and 30 evenly spaced horizontal rows (fig. 17). The origin of the grid is the bottom left corner. Radial spacing of the columns expands logarithmically from 0.14 ft (near the well) to a maximum of 50 ft. This discretization produces a fine grid near the pumped well where fluid pressure and concentration gradients are expected to be large. Vertical spacing of the rows was 20 ft. This discretization was selected to minimize the number of rows while approximately positioning nodal locations to adequately represent the eight hydrogeologic units of the multilayered aquifer. The simulated area is 3,000 ft in radius and 600 ft in depth. Greater radial extents of 6,000 and 10,000 ft also were simulated. The greater model extents did not affect the pressures and concentrations at the lateral boundary, because of the type of boundary condition selected; therefore, the smaller model region was selected for further numerical analysis. Boundary conditions will be discussed in a later section of the report.

Temporal Discretization

Two different temporal discretizations were used. One was used for the aquifer-test simulations and the other for the water-quality change simulations.

The 72-hour aquifer test and 48-hour recovery period were divided into four separate stress periods. Stress period 1 corresponds to the initial 14.33 hours of brackish-water withdrawal prior to the unexpected cessation of pumping. Ten equal time steps of 1.43 hours were simulated. Stress period 2 corresponds to the 2.5 hours when the pump was off. Two equal time steps of 1.25 hours were simulated. Stress period 3 corresponds to the remaining 55 hours of brackish-water withdrawal during the aquifer test. Twenty equal time steps of 2.75 hours were simulated. Stress period 4 corresponds to the 48 hours of recovery following the 72-hour brackish-water withdrawal. Twelve 4-hour time steps were simulated. These time-step scenarios were selected to generate temporal output to match field data collected during the aquifer test.

Temporal discretization for simulating water-quality changes was achieved by using the automatic time stepping capability of the HST3D numerical code. The minimum time-step length was set at 0.1 day to accommodate temporal changes in the boundary conditions and pumping changes. The maximum time-step length was set at 14 days to generate temporal output to match field data. The actual time increment used for each time step is automatically selected by the model, within the specified range, to reach the target pressure and concentration limits specified by the user.

Boundary Conditions Used to Simulate the Aquifer Test

The extent of the model area, delineated by the boundaries, represents a region that extends beyond the radial distance where water levels in observation wells were affected by pumping the brackish production well during the 3-day aquifer test. Four types of boundary conditions were implemented.

The top and bottom of the model were designated as specified pressure boundaries corresponding to the top of the surficial aquifer system and the base of semi-confining unit 3. For the purposes of simulating the

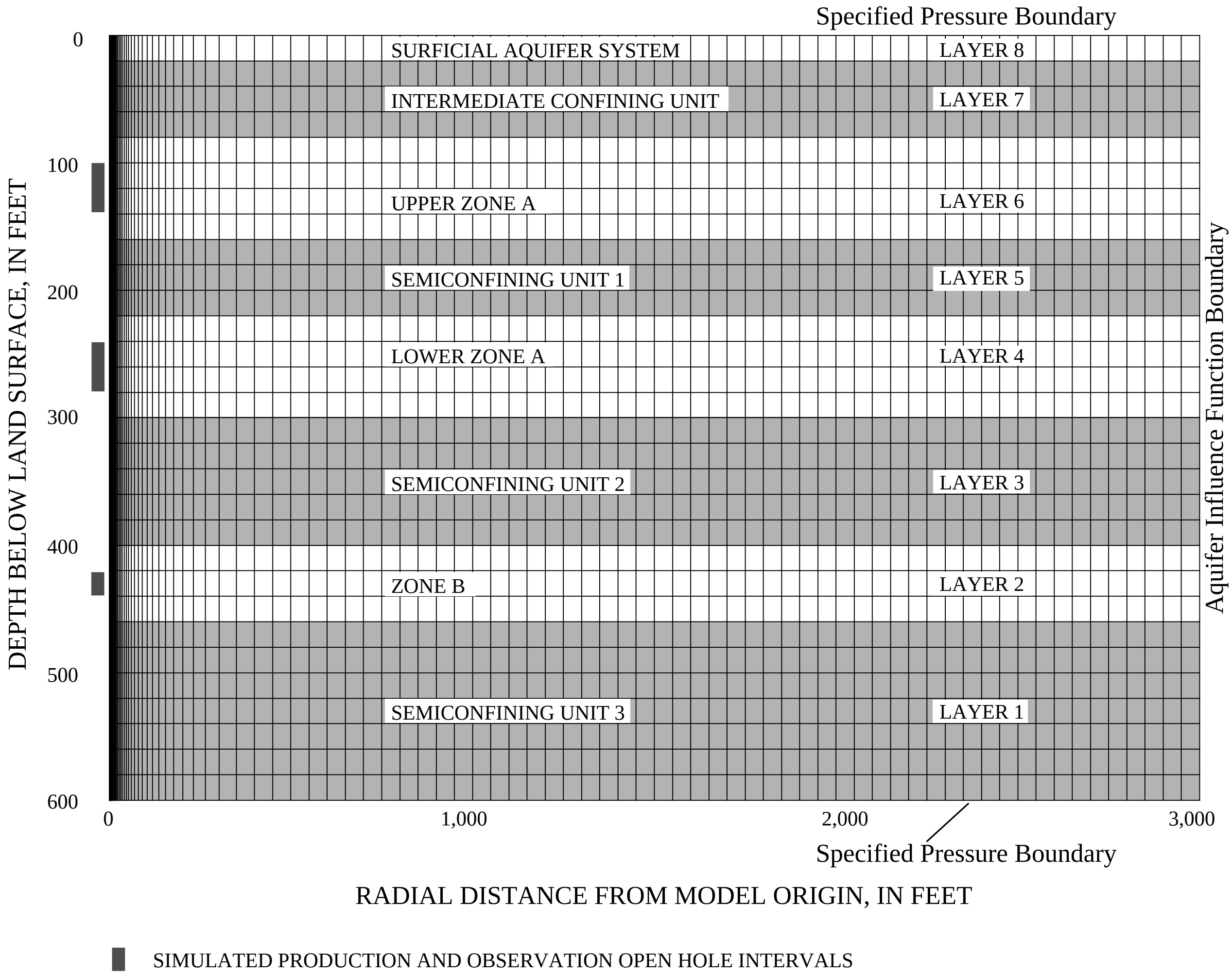


Figure 17. Model grid, simulated open-hole interval, and boundary conditions.

aquifer test, it was assumed that no background vertical leakage occurred, therefore hydrostatic pressure conditions were deemed appropriate. A specified hydrostatic pressure of 0.0 pound per square inch (lb/in^2) was assigned to the upper boundary. This boundary type for the top of the model was deemed reasonable because the water table in the surficial aquifer system (1) did not change during the aquifer test; and (2) has not changed, on average, during the period 1987-95 in the vicinity of Dunedin. A specified hydrostatic pressure of 259.34 lb/in^2, equivalent to the pressure exerted from a 600-ft column of freshwater in the overlying formations, was assigned to the lower boundary. The pressure was calculated using the density of freshwater, because water-quality changes did not occur during the aquifer test. This boundary type for the base of the model was deemed reasonable, because the semiconfining unit 3 has a hydraulic conductivity that is three orders of magnitude less than the overlying permeable zone.

The inner cylindrical boundary has two types of boundary conditions. The brackish production well was simulated at the radial origin corresponding to rows 17 and 18 and represents the producing interval of lower zone A. The rows on the inner cylindrical boundary that represent the cased interval of the well were assigned a no-flow condition.

The outer cylindrical boundary is defined by a transient flow, aquifer-influence function that utilizes the Carter-Tracy approximation to compute flow rates between the inner, discretized aquifer region and an infinite homogeneous outer region where aquifer properties are only generally known. The primary benefit of using the aquifer-influence function boundary condition is the reduction in discretized area while simulating an infinite aquifer. This option reduces the computer storage and computation time needed for simulation (Kipp, 1987, p. 59).

Boundary Conditions Used to Simulate Water-Quality Changes

The model area, delineated by the boundaries, encompasses a region that extends beyond the radial distance affected by production well withdrawals at the Dunedin water plant. Historical water-level and chloride-concentration data indicate that well-field pumpage results in localized drawdowns (potentiometric-surface depressions) and circular isochlors extending small radial distances from production well clusters. Therefore, the extent of the model area was chosen to be the same as the aquifer-test simulation.

Four types of boundary conditions were implemented. The simulated vertical extent of the model area was the same as for the aquifer-test simulation. A specified-pressure and specified-solute concentration boundary was designated at the top of the model, because average water levels and water quality in the surficial aquifer system do not appear to have changed in the vicinity of Dunedin. For the purposes of simulating water-quality changes due to production well pumping, the dynamic effects of leakage and multi-density flow preclude the use of hydrostatic pressures; therefore, density-dependent pressures were calculated as input for the lower specified-pressure boundary. The upper boundary was assigned a constant pressure of 0.0 lb/in^2 and a constant-solute concentration value, represented as a mass fraction, was set at 0.0 corresponding to a 25-mg/L chloride concentration, which is the background chloride concentration. The bottom boundary was assigned a constant pressure and solute concentration corresponding to the base of semiconfining unit 3. The pressure on the bottom boundary was set at 243.51 lb/in^2. This value was calculated using the water-level and chloride-concentration data at the base of semiconfining unit 3 and is different from 259.34 lb/in^2 (used to simulate the aquifer test) due to the consideration of the density differences in the aquifer. A constant-solute concentration value, represented as a mass fraction, was set at 0.63 corresponding to a chloride concentration of 12,000 mg/L. A mass fraction value of 1.0 corresponds to a chloride concentration of 19,000 mg/L. The base of the model coincides with the approximate location of saline water below which the aquifer has 100 percent saltwater.

The inner cylindrical boundary has two types of boundary conditions. Various pumping scenarios were simulated by changing the input well definition representing the different open-hole intervals. The rows on the inner cylindrical boundary that represent the cased interval of the well were assigned a no-flow condition.

The outer cylindrical boundary is characterized as a transient flow, aquifer-influence function that utilizes the Carter-Tracy approximation to compute flow rates between the inner, discretized aquifer region and an infinite homogeneous outer region where aquifer properties are only generally known. The assigned pressure distribution along the outer cylindrical boundary was calculated using water-level and chloride-concentration data collected as part of this study. The primary benefit of using the aquifer-influence function boundary condition is the reduction in simulated area size. This option reduces the computer storage and computation time needed for simulation.

Input Parameters

The validity of selected input parameters used in the simulations and presented in this report were evaluated using sensitivity analysis. The purpose of the sensitivity analysis was (1) to independently assess the effect of varying initial hydraulic parameter values and (2) to provide a match between simulated and observed water-level and chloride-concentration data.

The initial simulations incorporated the best estimates of hydraulic properties derived from aquifer-test analyses, laboratory core analyses, and geophysical log interpretations. Data were compiled from previous studies in Pinellas County (Hickey, 1982; Knochenmus and Thompson, 1991) and collected as part of this study. The sensitivity analysis involved systematically adjusting the initial input parameters and assessing their effects on model results. These effects were evaluated by comparing simulated and observed water-level changes during the brackish production well aquifer test. Input parameters used to simulate the aquifer test were those input parameters that resulted in a reasonable water-level match. Selected model input parameters are listed in table 2.

The initial chloride-concentration distribution used in the water-quality-change simulations were estimated from (1) water-quality data collected as part of this study and (2) historical chloride-concentration data compiled by Dunedin personnel as part of their water-use permit requirements. Sensitivity analysis was used to generate an input data set by systematically adjusting initial parameter values. The sensitivity analysis focused on matching simulated and observed water-level and chloride-concentration data for the period 1970-94. Input parameter values used to simulate this 25-year period are listed in table 2.

Wells

The pumped well simulated in the aquifer test model is the brackish production well. The well is located at the radial origin of the model. The open-hole interval of the well is defined in terms of row numbers. The simulated open-hole length was 40 ft corresponding to rows 17 and 18 and is equivalent to a depth interval from 240 to 280 ft below land surface. This interval corresponds to the approximate location of the major producing zone in lower zone A. Variable discharge rates were used to simulate the aquifer test. The discharge rates for the four stress periods were 670, 0, 690, and 0 gal/min, respectively. These correspond to changes in withdrawal rates during the aquifer test. The model distributes the total simulated discharge among the cells based on cell location, hydraulic conductivity, and well-completion factor. The well-completion factor defines the amount of flow to the well from individual cells in response to pressure differences between the simulated well bore and aquifer. A well-completion factor of 1 was assigned to the two pumped cells.

The simulated open-hole interval of the pumped well for the 25-year chloride concentration history match approximates the location of the water-producing zone in upper zone A in the vicinity of the water plant.

Table 2. Model-input values and model-derived hydraulic parameters

[Constant parameters: water temperature, 75 degrees Fahrenheit; viscosity, 0.8904 centipoise; molecular diffusivity, 9.3 x 10^{-5}; porosity, 0.3; matrix compressibility, 6.2 x 10^{-6} cubic inches per pound; longitudinal/transverse dispersivity, 12.5/2.5 feet; --, no data; ft^2, square foot; ft/d, feet per day; d^{-1}, per day; lb/ft^3, pounds per cubic foot; mg/L, milligrams per liter; lb/in^2, pounds per square inch; shaded columns or * represent input values used for brackish-water simulations.]

Hydrogeologic unit and top/bottom boundaries	Intrinsic permeability (ft^2)/ hydraulic conductivity (ft/d)	Storage coefficient	Leakance (d^{-1})	Specific weight of water (lb/ft^3)	Scaled solute mass fraction / chloride concentration (mg/L)	Starting water-level elevation (ft) / pressure (lb/in^2)
Top specified pressure boundary	--	--	--	62.241	0.000 / 25	50 / 0.0
Surficial aquifer	3.9 x 10^{-11} /10	3.0 x 10^{-1}	--	62.241	0.000 / 25	50 / 0.0
Intermediate confining unit	3.9 x 10^{-16}/ 0.0001	1.9 x 10^{-4}	1.7 x 10^{-6}	62.253	0.000 / 25	--
Upper zone A	1.6 x 10^{-09} / 400	2.0 x 10^{-4}	--	62.260	0.001 / 44	4.5 / 32.43
Semiconfining unit 1	7.8 x 10^{-13} / 0.2	1.3 x 10^{-4}	3.3 x 10^{-3}	62.280	0.004 / 100	--
Lower zone A	3.9 x 10^{-10} / 100	2.0 x 10^{-4}	--	62.570	0.010 / 215	6.0 / 93.68
Semiconfining unit 2	7.8 x 10^{-13} / 0.1 *(0.2)	3.1 x 10^{-4}	2.0 x 10^{-3}	62.590	0.020 / 400	--
Zone B	3.9 x 10^{-10} / 100	1.6 x 10^{-4}	--	62.990	0.260 / 5,000	6.5 / 163.7
Semiconfining unit 3	3.9 x 10^{-13} / 0.1	3.9 x 10^{-4}	7.1 x 10^{-3}	63.410	0.630 / 12,000	--
Bottom specified pressure boundary	--	--	--	63.410	0.630 / 12,000	2.5 / 243.5

The well is located at the radial origin of the model. The open-hole interval of the well is defined in terms of row numbers. The simulated open-hole length was 40 ft corresponding to rows 24 and 25 and is equivalent to a depth interval from 120 to 160 ft below land surface. This interval corresponds to the approximate location of the major producing zone in upper zone A. Discharge rates were varied yearly (25 times) during the simulation period (1970-94) corresponding to the average annual rate from the six water plant production wells. The pumpage data were provided by the city of Dunedin and the SWFWMD. The averaged discharge rates ranged from 0.088 to 0.314 Mgal/d. A well-completion factor of 1 was assigned for the two pumped cells.

In all scenarios, the pumped well is located at the radial origin of the model. Open-hole intervals for the well tapping upper and lower zone A are the same as described above. For the simulations used to estimate water-quality changes in response to brackish-water development, the following well definitions were utilized:

1. Case 1, long-term (30 years) brackish-water withdrawals from lower zone A to approximate aquifer response to brackish-water production located away from freshwater production-well clusters;
2. Case 2, long-term, simultaneous withdrawal from both the freshwater (upper zone A) and brackish-water (lower zone A) producing zones at equal rates; and
3. Case 3, long-term, simultaneous withdrawal from both the freshwater and brackish-water producing zones at unequal rates.

Case 1:

A steady discharge rate of 300 gal/min was used to simulate 30 years of brackish-water withdrawal from lower zone A, because it is the expected average permitted withdrawal rate. A well-completion factor of 1 was assigned to the two cells representing the open-hole interval in lower zone A.

Case 2:

Two discharge rates of 300 and 600 gal/min (150 and 300 gal/min from each producing zone) were independently tested. Equal discharge from upper and lower zone A was simulated to assess the effects of combined fresh- and brackish-water withdrawals. The well bore used to simulate combined withdrawals from upper and lower zone A was approximated by designating two open-hole intervals in a single well. The allocation of flow to the well from upper and lower zone A was accomplished by specifying a well-completion factor for each node representing the open-hole intervals. This procedure was necessary because only one pumping well can be simulated in a cylindrical coordinate system. To achieve equal discharge rates from upper and lower zone A, well completion factors of 0.25 and 1.0 were assigned to the cells representing upper and lower zone A, respectively. Assignment of these well completion factors to upper and lower zone A was an adjustment for the differences in permeability values, because upper zone A is four times more permeable than lower zone A.

Case 3:

Steady discharge rates of 300 and 600 gal/min (at unequal volumes from the two producing zones) were selected for simulating water-quality changes in response to different pumping scenarios. Well-completion factors were assigned a value of 1 or less in the cells representing the open-hole interval in upper zone A to adjust the allocation of flow for the various pumping scenarios.

Observation Wells:

Observation wells also were simulated. The locations of observation wells approximate the locations of the production 14 and brackish monitor observation wells. The observation wells were located 61 (column 32) and 70 ft (column 33), respectively, from the brackish production well. These simulated observation wells have 20-ft completion intervals corresponding to row 25 and 9, respectively. For the water-quality change simulations, observation wells penetrated upper zone A, lower zone A, and zone B and were located 5 ft from the pumped well. The simulated open-hole intervals are rows 25, 18, and 9, respectively.

MODEL ANALYSIS OF THE AQUIFER TEST

Numerical simulation of the aquifer test data provided an alternative method for calculating hydraulic properties of the permeable zones and semiconfining units by matching simulated and observed water-level changes in the pumped well (lower zone A) and observation wells above (upper zone A) and below (zone B). However, emphasis was not placed on obtaining an exact water-level match but rather on gaining an understanding of the dynamics of the flow system. Hydrostatic pressure conditions were assumed. Under hydrostatic conditions, initial water levels in the aquifer are assumed to be at equilibrium and, therefore, simulated pressure changes are only in response to brackish production well withdrawals. This approach is used for “drawdown” simulations. In this type of simulation, changes in head are of interest, rather than absolute values of head. The principle of superposition is used to justify calculation of drawdown from an arbitrary horizontal datum that represents the initial head distribution. This initial head distribution represents dynamic average steady-state conditions (Anderson and Woessner, 1992, p. 199-200). The advantage of superposition is that the effects of the aquifer test can be evaluated without accounting for other unknown stresses acting on the ground-water system (Reilly and others, 1987). Model results are discussed in the following section of the report.

Results

Model results were evaluated by comparing simulated and observed water levels and by a flow field analysis using plots of vector fields. Observed and simulated water-level changes in the brackish monitor (zone B) and production 14 (upper zone A) wells are depicted in figure 18. To get these results, only slight changes were made to the initial input data. Model-simulated changes in zone B parallel those observed in the brackish monitor well during all four phases of the aquifer test. Model-simulated changes in upper zone A match best during the recovery phase of the test. The observed water levels are apparently influenced by changes in (1) tide stage at the coast and (2) pumping rates in the well field. Response to tide-stage changes are indicated by the cyclic rise and fall of water levels in both the production 14 and the brackish monitor

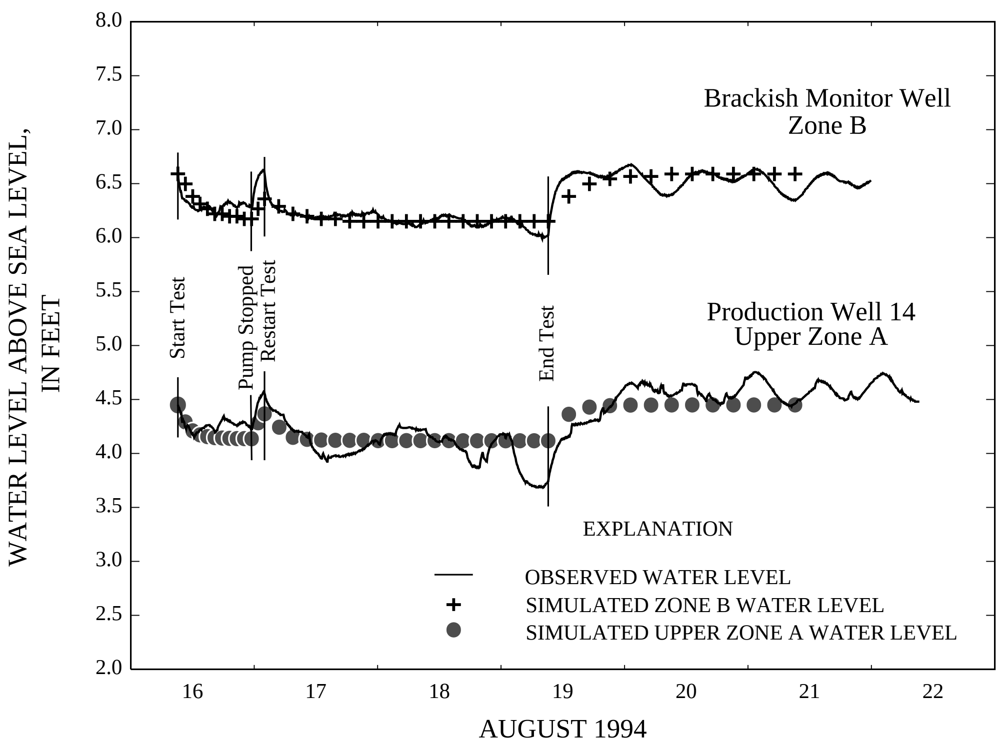


Figure 18. Measured and model-simulated water levels in the brackish monitor and production 14 wells.

wells (fig. 18). The effects of pumping-rate changes in the nearby production wells are indicated by: (1) the increased drawdown (falling water levels) in production well 14 at 200 minutes into the test (fig. 16) corresponding to a 200 gal/min increase in discharge from the water plant production wells; (2) the rapid rise in water levels in production 14 and brackish monitor wells about 14 hours into the test when the pump in the brackish production well unexpectedly stopped; and (3) the rapid rise in water levels at the end of the 3-day aquifer test. As indicated in figures 16 and 18, the water level in production well 14 responds to pumping changes in both upper and lower zone A.

Simulated water-level changes in the brackish production well compare favorably with observed changes. Observed water levels indicate rapid response and stabilization. Twenty ft of drawdown occurred within the first minute of the test. This drawdown was about 80 percent of the total drawdown (25 ft) during the test. Simulated water levels in the pumped well also exhibited a rapid response to pumping and a simulated total drawdown of about 24 ft. Model derived hydraulic conductivities, storage coefficients, and leakance of the hydrogeologic units are listed in table 2.

The flow field generated by the model at the end of the simulated 3-day pumping period is depicted in figure 19. The figure supports a favorable numerical solution of the flow field because vectors indicate relatively uniform flow and point in the direction of the known vertical head gradients in the study area. Flow was nearly lateral in the permeable zones and nearly vertical in the semiconfining units. Near the simulated pumped well in lower zone A, fluid movement is downward from upper zone A and upward from zone B as a result of lowering the head 24 ft in lower zone A. Inflow occurs along the upper, lower, and outer boundaries. The velocity-vector field in the surficial aquifer system and intermediate confining unit is not shown because the velocities are low. Simulations indicated that the selection of hydraulic conductivity assigned to the hydrogeologic layers above and below the pumped zone affect water-level responses in the pumped zone and overlying and underlying permeable zones. These changes in water-level responses are discussed in the following section of the report.

Sensitivity Analysis

Sensitivity analysis was the tool used to gain an understanding of the role of each parameter in generating model results in response to changes in individual input parameters. Changes in model results provide insight as to the degree that changes in parameters may affect the flow field. Input parameters including porosity, bulk matrix compressibility, and intrinsic permeability were individually varied over a reasonable range of values to determine the sensitivity of the model to these parameters.

The input values for porosity and bulk matrix compressibility had little effect on the model results. Sensitivity analysis of the bulk matrix compressibility indicates that an order of magnitude reduction or increase in value only affected simulated water levels immediately following changes in the simulated withdrawal rates. A reduction in bulk matrix compressibility caused a more sluggish water-level response. An increase in bulk matrix compressibility caused a masking of the water-level response to pumping-rate changes.

The model was most sensitive to intrinsic permeability. Hydraulic conductivity (K) and intrinsic permeability (k) values are listed in table 2. Hydraulic conductivity (K) can be defined in terms of intrinsic permeability (k) using a relation presented in Freeze and Cherry (1979, p. 29). The relation is

$$K = \frac{k\rho g}{\mu}$$

where,

μ is dynamic viscosity of the fluid in units M/LT,
ρ is fluid density in units M/L^3,
g is gravitational acceleration in units L/T^2,
k is intrinsic permeability in units L^2, and
K is hydraulic conductivity in units L/T.

The following discussion will use the term hydraulic conductivity as a surrogate for intrinsic permeability because hydraulic conductivity is the commonly used parameter of interest. The effects of hydraulic conductivity on simulated water levels are illustrated in figure 20. Water levels in both upper zone A (production 14) and zone B (brackish monitor) were least affected by changes in hydraulic conductivity in the intermediate confining unit and in semiconfining unit 3. The greatest divergence of simulated from measured water levels in upper zone A occurred from changes in hydraulic conductivity in upper zone A and semiconfining unit 1.

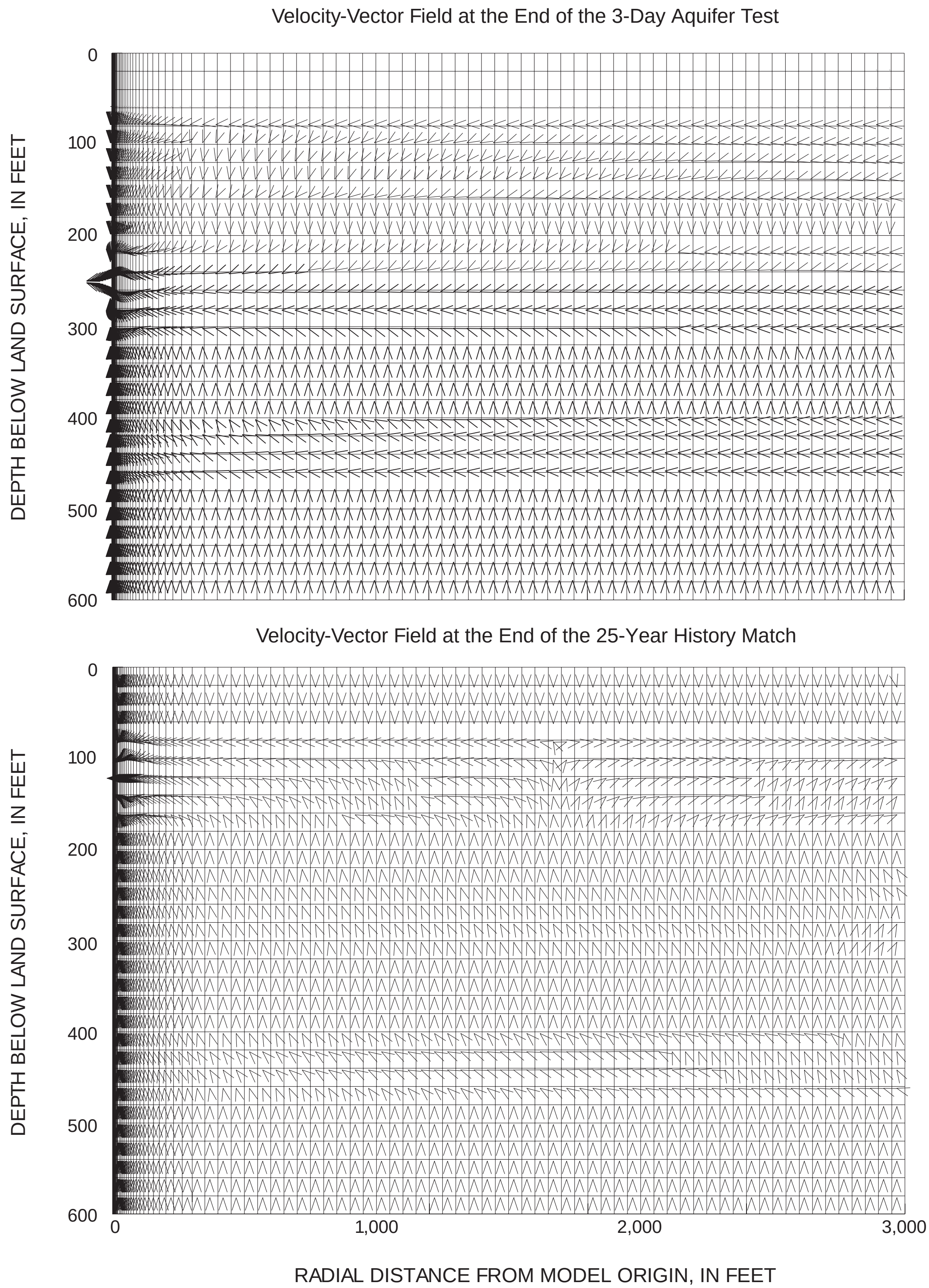


Figure 19. Velocity-vector field in a radial section at the end of the 3-day aquifer test and at the end of the 25-year history match. (A schematic of the model grid and hydrogeologic layers corresponding to the gridding on this figure is shown in figure 17.)

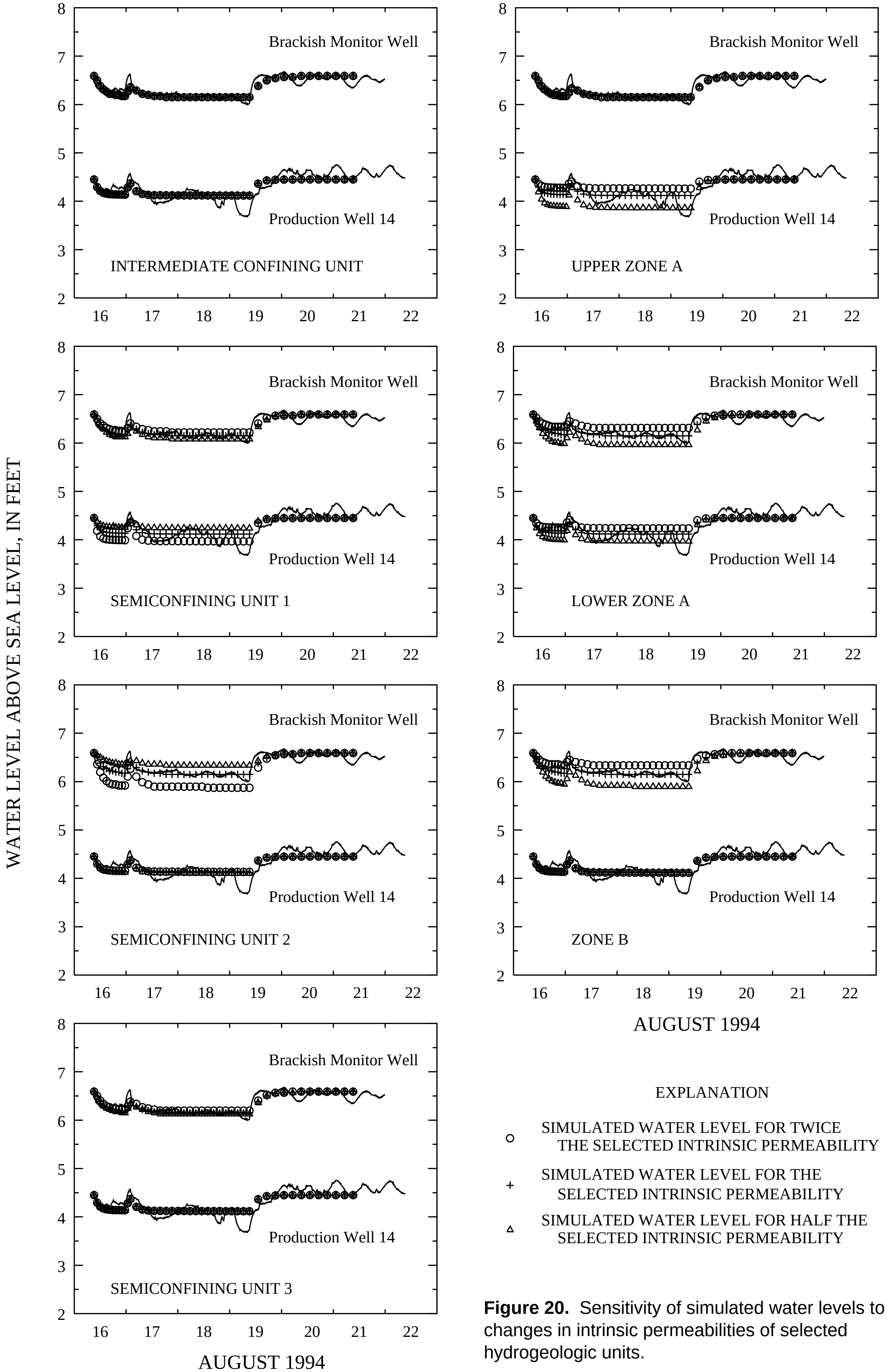


Figure 20. Sensitivity of simulated water levels to changes in intrinsic permeabilities of selected hydrogeologic units.

The greatest divergence of simulated from measured water levels in zone B occurred from changes in hydraulic conductivity in zone B and semiconfining unit 2. Divergence of simulated from measured water levels in both upper zone A and zone B occurred from changes in hydraulic conductivity in lower zone A. This implies that small changes in hydraulic conductivity, with the exception of the intermediate confining unit and semiconfining unit 3, result in a significant divergence of simulated from measured water levels. Model results indicate that the hydrogeologic system underlying the city of Dunedin water plant was reasonably simulated because only a narrow range of hydraulic conductivity values mimic the observed hydraulic response in the multilayered aquifer.

MODEL ANALYSIS OF HISTORICAL CHLORIDE-CONCENTRATION CHANGE

The purpose for simulating changes in chloride concentration in ground water during the 25-year simulation period (1970-94) was to assess how well model results compared to historically observed chloride-concentration changes in water from the Dunedin water plant production wells. If a reasonable match can be accomplished, then the model can be used to analyze the response of the aquifer to past and present ground-water withdrawals and to estimate the responses of the aquifer to future ground-water development. The model-derived hydraulic parameters obtained from the aquifer-test simulation were used as the initial distribution of the hydraulic characteristics of the permeable and semiconfining units comprising the uppermost Upper Floridan aquifer underlying Dunedin. However, one modification to the input parameters was necessary. An intrinsic permeability value of 7.8×10^{-13} ft^2 (hydraulic conductivity value of 0.2 ft/d) was utilized as input for semiconfining unit 2 after chloride concentration trends could not be adequately simulated using a value of 3.9×10^{-13}ft^2. Several attempts were made to resolve this modification including rerunning the aquifer-test simulation; however, when using the larger value the observed drawdown in the zone B could not be duplicated. This may be due to differences in model results for a 3-day versus 25-year simulation period.

Approximately 25 years of record (1970-94) for pumpage, water levels, and chloride concentrations in upper zone A were available for comparison. However, historical chloride-concentration data for deeper zones in the aquifer had to be estimated, because no data exist for the hydrogeologic layers below upper zone A. The initial chloride-concentration values for the deeper zones, computed as a mass fraction distribution, were set equal to the estimated chloride-concentration distribution in native waters, assumed to have existed in 1970.

The annual pumping rate used in the simulation was the average rate of the six water plant wells (numbers 6, 9, 13, 14, 15, and 16). The rationale for using an average value from the six wells is that observed water-level and water-quality data from individual wells are probably influenced by the combined effects of several adjacent pumped wells in production well clusters. This phenomena was indicated by evaluating simulated chloride changes using only production well 14. During the period 1970-94, this well was out of service for several years. During the out-of-service periods, simulated chloride-concentration values stabilized while observed concentrations continued to rise; thus, the rationale for using an average pumping rate from the six water plant wells.

Results

Model results were evaluated by comparing simulated to observed water-level and water-quality changes in upper zone A. In addition, a flow field analysis using plots of velocity vectors was assessed. For ease of model evaluation and comparison, the simulated pressures and mass fraction values were converted to water levels and chloride concentrations, respectively. Because water levels remained fairly constant throughout the period 1970-94, discussion of the model results focuses on comparisons between observed and simulated chloride concentrations. The simulated chloride-concentration change was compared to the observed chloride-concentration change in each of the six production wells (fig. 21).

In general, simulated and observed water levels and chloride concentrations compared favorably; however, comparisons were slightly different among the water plant wells. The most favorable comparisons were for production wells 13 and 14. These two wells are located nearest the centroid of pumping for the water plant production-well cluster.

Comparisons for production wells 15 and 16 were poorest during the period 1970-79. Simulated chloride concentrations tended to be substantially lower (less than 60 mg/L) than observed chloride concentrations during this period. These two wells are located north

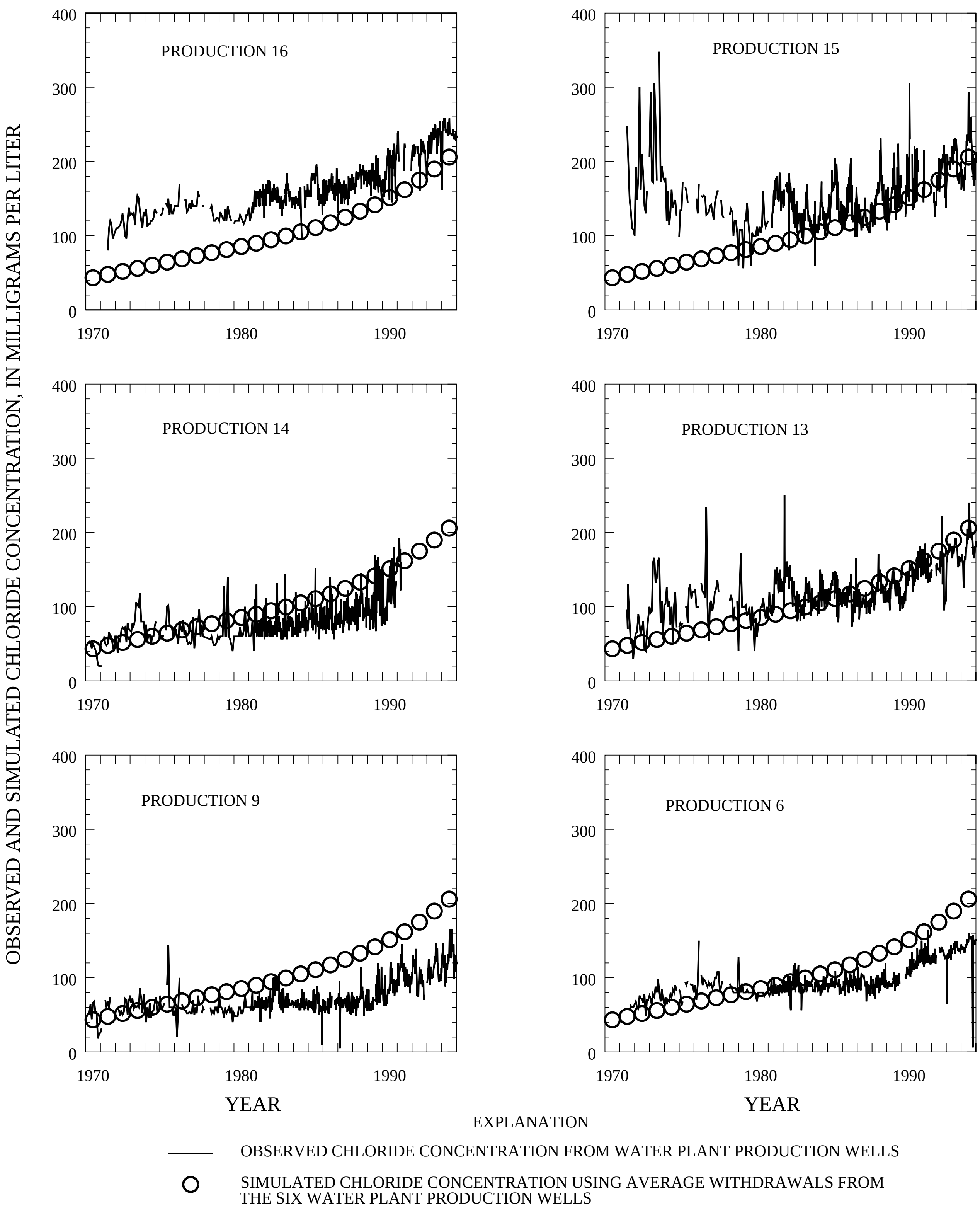


Figure 21. Comparison of measured and simulated chloride concentrations from the water-plant wells, 1970-94.

of the brackish-water test site. It should be noted that the earliest observed chloride concentrations are elevated relative to other production wells in the well field. These elevated chloride concentrations are probably the result of measurement error, because the values are an order-of-magnitude higher during this period than elsewhere in the well field.

Comparisons for production wells 6 and 9 were poorest during the period 1983-94. Simulated chloride concentrations tended to be substantially higher (greater than 50 mg/L) than observed chloride concentrations during this period. These two wells are located south of the brackish-water test site and farthest from the centroid of pumping. The poor duplication between simulated and observed chloride-concentration changes in production wells 6 and 9 is because these wells are less affected by well interference due to their distance from the centroid of pumping.

Simulated chloride-concentration data from all of the water plant production wells show a break-in-slope in the late 1980’s corresponding to a break-in-slope in the observed chloride-concentration data. In general, the chloride-concentration trends are similar and a comparison between simulated and observed concentrations is reasonably good. This favorable comparison lends some confidence in using the transport model to assess the association between ground-water withdrawals from and chloride changes in upper zone A.

Flow was nearly lateral in the upper zone A and zone B permeable zones (fig. 19). Fluid movement is downward from the surficial aquifer system and upward from all units below upper zone A. Inflow occurs along the upper and lower boundaries. Outflow occurs along the outer boundary in upper zone A. A flow divide occurs in upper zone A at a radial distance of about 1,600 ft. This may be the result of the circulation or circular convection caused by pumping a multilayered, multidensity aquifer. Circular convection has been shown to be a major process influencing the distribution of solute in space and time (Hickey, 1989, p. 1494). The simulated flow divide appears to be consistent with the observed localized potentiometric-surface depressions that exist in the Dunedin well field.

Sensitivity Analysis

Sensitivity analysis was the tool used to determine the sensitivity of the model-predicted chloride changes to model input and to assess the uncertainty of estimated aquifer hydraulics and transport properties. The analysis provides a means to identify the most important aquifer characteristics. Input parameters that were tested include intrinsic permeability (hydraulic conductivity), dispersivity, and mass fraction (chloride concentration) distribution. These parameters were individually varied over a reasonable range of values to determine the sensitivity of the model results to these parameters. The model results were not sensitive to changes in parameter values for dispersivity.

Model results indicated that the selection of hydraulic conductivity was the most important factor and produced the greatest changes in the simulated chloride concentrations; therefore, the discussion of the sensitivity analysis emphasized this parameter. The effects of intrinsic permeability (hydraulic conductivity) on simulated chloride concentrations are shown in figure 22. Divergence of simulated from measured chloride concentrations in upper zone A occurred from changes in hydraulic conductivity in the three semiconfining units. Greatest divergence occurred from changes in hydraulic conductivities of semiconfining units 1 and 2. Small divergence occurred from changes in hydraulic conductivity in zone B and semiconfining unit 3. No measurable divergence occurred from changes in hydraulic conductivity in upper and lower zone A. These findings imply that small changes in simulated hydraulic conductivity for the semiconfining units result in a significant divergence of simulated from observed chloride concentrations. The importance of the semiconfining units as a mechanism for retarding the vertical movement of higher salinity ground water is significant. The model results show that the derived hydraulic parameters and water-quality distribution are reasonable estimates for the hydrogeologic system underlying Dunedin.

MODEL ANALYSIS OF LONG-TERM BRACKISH-WATER WITHDRAWALS

Numerical simulation also was used to estimate future trends in chloride concentrations in the uppermost Upper Floridan aquifer resulting from brackish-water development. To learn more about the effects of future pumping on chloride-concentration and water-level changes, the model was run for 30 years using three different pumping scenarios. A 30-year time period was selected for economic purposes (typical amortization period) and, more importantly, because historical chloride trends in water from upper zone A

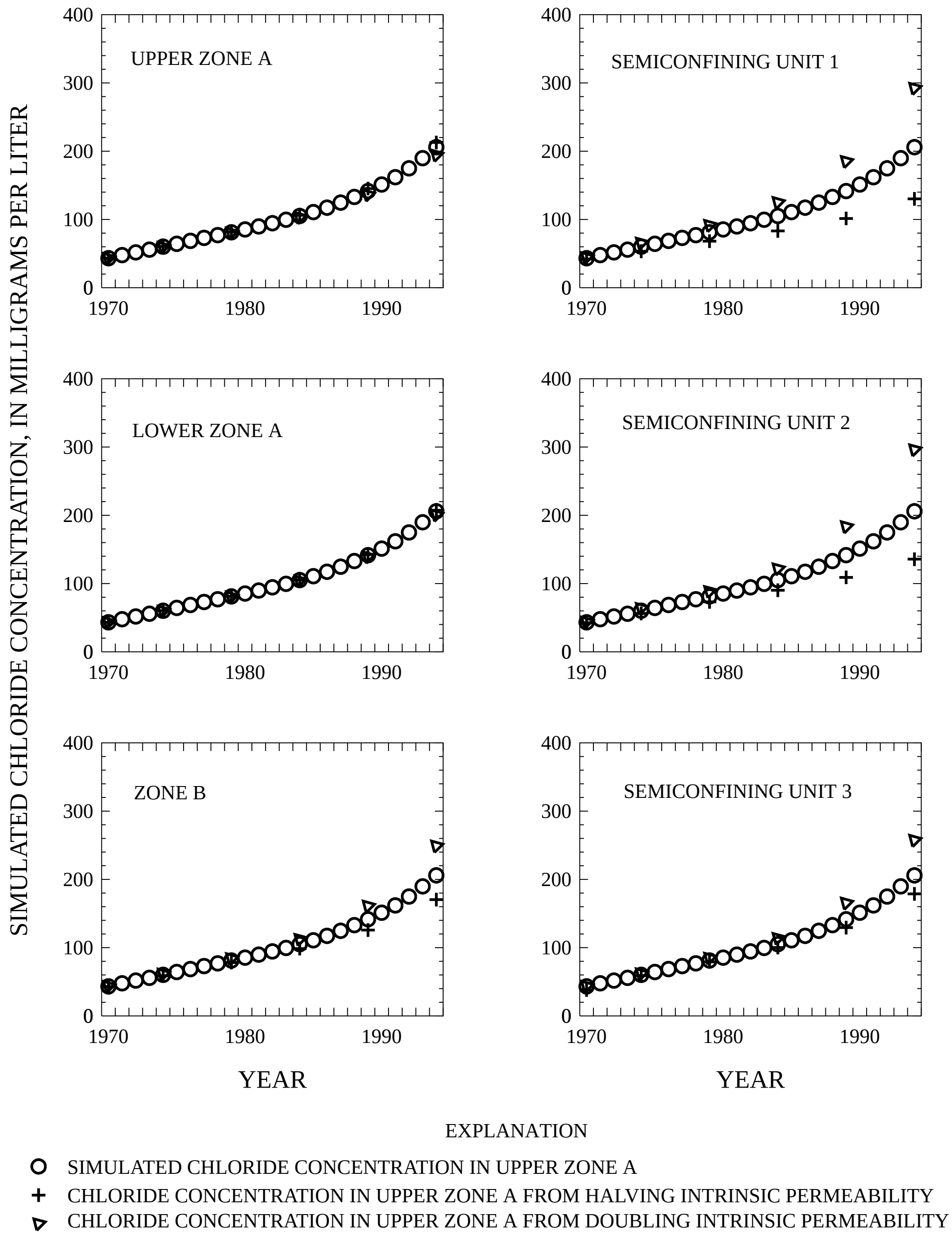


Figure 22. Sensitivity of simulated chloride concentration to changes in intrinsic permeabilities of selected hydrogeologic units.

indicated that a break-in-slope did not occur until after 18 years of pumping. Field data and model analysis of historical water-level and chloride-concentration changes (discussed in previous sections) indicate that the pressure field rapidly responds to ground-water withdrawals (on the order of minutes); whereas, the concentration field may take years to equilibrate.

The effects of brackish-water development on water-level and chloride-concentration changes in upper and lower zone A and zone B were evaluated using three different pumping scenarios, including brackish-water withdrawals away from fresh-water production well clusters and simultaneous pumping from upper and lower zone A. These scenarios are designated as cases. In case 1, a single well in lower zone A was simulated to assess the effects of pumping only brackish water at a rate of 300 gal/min. In case 2, a single well open to upper and lower zone A was simulated to assess the effects of pumping equal volumes of freshwater and brackish water at total rates of 300 and 600 gal/min. In case 3, a single well open to upper and lower zone A was simulated to assess the effects of pumping unequal volumes of freshwater and brackish water from upper and lower zone A at total rates of 300 and 600 gal/min and to assess if an optimal pumping scenario exists that may limit these changes. The initial pressure and mass-fraction distribution used in these simulations is the resultant distribution after the 25-year simulation and approximates the conditions for 1995, the year that the first brackish production well was completed.

Results

Model results are discussed in terms of possible changes that could occur in the Upper Floridan aquifer from the addition of brackish-water withdrawals. For ease of model evaluation and comparison, the simulated pressures and mass-fraction values were converted to water levels and chloride concentrations, respectively.

Case 1--Single well open to lower zone A

Simulation results from the 300 gal/min pumping rate from lower zone A during the 30-year simulation period indicated that brackish-water development does not influence the water quality in upper zone A. Chloride concentrations stabilize in upper zone A when lower zone A is pumped; however, chloride concentrations rapidly rise in lower zone A and may exceed 4,000 mg/L after 30 years of brackish-water withdrawals (fig. 23). Pumping from lower zone A results in a lower head in lower zone A than in either upper zone A or zone B. The head difference is greater between zone B and lower zone A (7 ft) than between upper zone A and lower zone A (4 ft). A slight break-in-slope in simulated chloride concentrations occurs after about 18 years. This break-in-slope may indicate that the hydrologic system is reaching an equilibrium between recharge of freshwater from upper zone A and recharge of higher salinity water from zone B. The chloride concentration also increased in lower zone B, probably as the result of the upward flow from the underlying semiconfining unit.

Case 2--Single well open to upper and lower zone A discharging equal volumes from each zone

The second pumping scenario was the simulation of equally distributed withdrawals from upper and lower zone A during a 30-year period (fig. 23). Two withdrawal rates, totaling 300 and 600 gal/min were simulated. Only slight differences in chloride-concentration trends for the three permeable zones occurred as the result of raising the total pumping rate from 300 to 600 gal/min. Simulated chloride concentrations in upper zone A initially decreased. After 10 years, however, chloride concentrations rose more rapidly. Chloride changes in upper zone A are probably the result of the continuation of current freshwater withdrawals from upper zone A rather than from pumping lower zone A. The chloride concentrations rapidly rose in lower zone A and exceeded 4,000 mg/L after 30 years of simultaneous fresh- and brackish-water withdrawal. The simulated chloride concentrations in lower zone A rose more rapidly in case 2 than in case 1. This more rapid rise is probably the result of reduced recharge from upper zone A. The simulated chloride-concentration trend in zone B is the same as in case 1.

Case 3-- Single well open to upper and lower zone A discharging unequal volumes from each zone

The third pumping scenario was the simulation of unequally distributed withdrawals from upper and lower zone A during a 30-year period (fig. 23). Two withdrawal rates, totaling 300 and 600 gal/min were simulated. More water was withdrawn from lower zone A (56 and 70 percent) than from upper zone A. Again, doubling the total pumping rate from 300 to 600 gal/min resulted in only slight changes in the chloride-concentration trends in the three permeable zones.

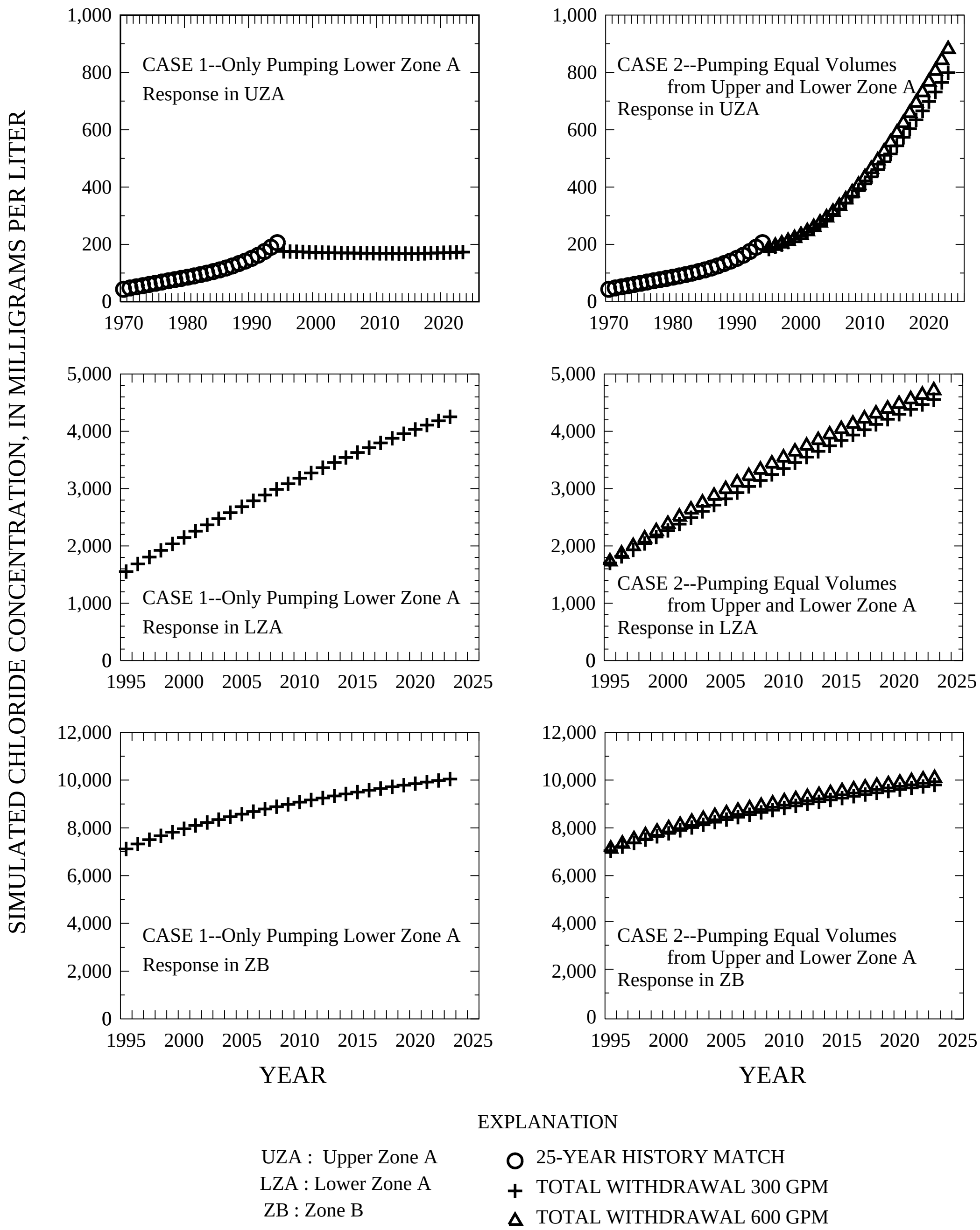


Figure 23. Model simulated chloride-concentration changes using various pumping scenarios from upper and lower zone A.

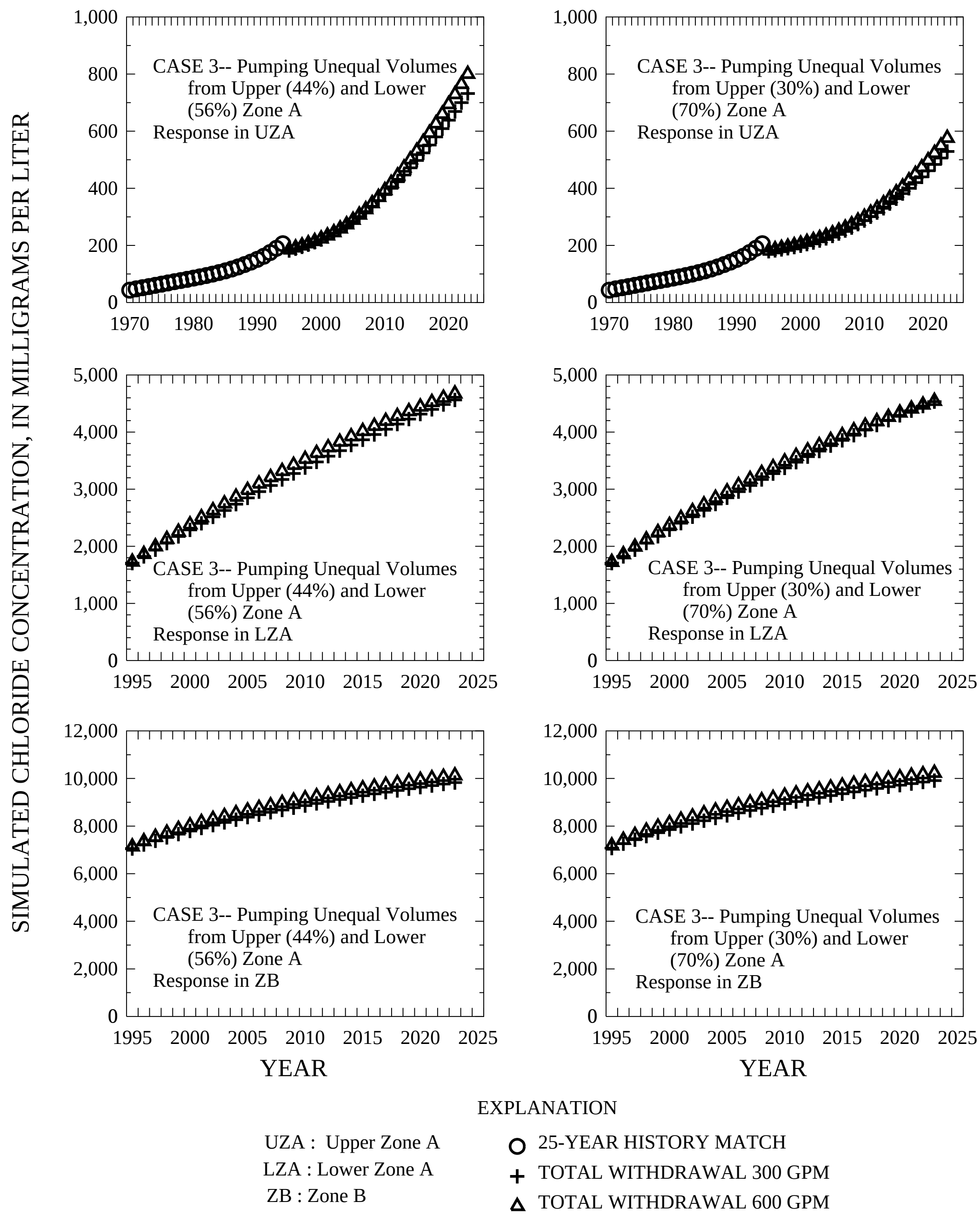


Figure 23.--Continued Model simulated chloride-concentration changes using various pumping scenarios from upper and lower zone A.

Pumping a larger percentage of the total pumpage from lower zone A resulted in flattening of the chloride trend in upper zone A. Increasing the pumpage to 70 percent from lower zone A resulted in a decrease in the final chloride concentration in upper zone A by about 25 percent. Simulated chloride-concentration trends in lower zone A do not appear to be affected by increasing withdrawal from the zone. The simulated chloride-concentration trend in zone B is the same as in the previous two cases.

Model results for case 1 indicate that pumping from lower zone A does not appear to negatively influence the chloride-concentration trends in upper zone A. This evaluation is reasonable because the head gradient between upper zone A and lower zone A is reversed when lower zone A is pumped. Water levels in lower zone A declined as much as 25 ft at a pumping rate of 600 gal/min. Therefore, development of the brackish-water resources should not adversely influence the freshwater zone (upper zone A) of the Upper Floridan aquifer. Water-quality changes in lower zone A may restrict development of large quantities of brackish water.

SUMMARY AND CONCLUSIONS

This report presents results of a study conducted to assess the fresh- and brackish-water resources in the uppermost Upper Floridan aquifer underlying Dunedin, Florida. The aquifer contains a lens of freshwater that is maintained by recharge from rainfall. This lens is relatively thin and is underlain by brackish and saline ground water. Historically, Dunedin has obtained enough ground water to provide potable water for its inhabitants. Although ample quantities of water are available, the water quality has changed. The effect on ground-water quality from concentrated withdrawals persists. Desalination of brackish ground water is one method used to enhance the ground-water resources. Evaluation of the fresh- and brackish-water resources required the delineation of producing zones and the water-quality distribution in the hydrogeologic units underlying Dunedin. A conceptual model of the hydrogeologic system was developed and tested using numerical simulation.

Geophysical, lithologic, water-level, and water-quality data that were collected as part of this study were used to assess the distribution of flow zones within the uppermost Upper Floridan aquifer underlying Dunedin. Through correlation of data, the hydrogeologic framework underlying the study area was conceptualized as a multilayered sequence of permeable zones and confining and semiconfining units. The presence of vertically spaced, discrete water-producing zones within these permeable zones was indicated. Generally, these producing zones occurred in the upper part of zone A (between 0 and 60 ft below sea level), the lower part of zone A (between 160 and 200 ft below sea level), and in zone B (between 350 and 400 ft below sea level). Based on the differences in water levels and water quality between producing zones in upper and lower zone A, the unit was divided into two permeable zones separated by a semiconfining unit. Upper zone A is the primary production zone in the Dunedin well field; however, many of the production wells penetrate both upper and lower zone A.

Evaluation of water-level data and potentiometric-surface maps indicated that, in northern Pinellas County, the Upper Floridan aquifer is best characterized as a local flow system. Pinellas 665 and Garden Street Triangle water-level data were used to evaluate water-level declines in response to municipal pumping in Dunedin and Clearwater and irrigation pumping in citrus groves. Water levels declined during the period 1957-75, stabilized during the period 1975-81, and have increased slightly since 1981. Pumping from the Dunedin well field increased from 1.2 to 4.9 Mgal/d during the period 1957-94, indicating that pumpage in the well field is probably not influencing water levels in the aquifer outside of Dunedin. Changes from the historical potentiometric surface in the study area do not appear to be substantial. Potentiometric-surface features such as the ground-water mound (divide) east of Dunedin and Clearwater and small radial depressions surrounding well clusters in these two cities have been common.

As part of this study eight water-level-collection sites were established in Dunedin. Water-level responses were highly variable among the observation wells, indicating a multilayered aquifer. These wells penetrate the different permeable zones in the aquifer.

The chloride concentrations in ground water underlying the study area are indicative of transitional type water and vary both vertically and laterally. Below lower zone A, water quality rapidly changes and saline water may occur at depths of 400 ft below sea level. In addition, zones of higher salinity water occur at shallow, discrete depths within zone A. Although delineation of the sources of chloride in the aquifer are difficult to quantify, it is highly unlikely that the only mechanism of transport is by lateral intrusion of modern seawater. A relation between chloride concentration and distance from St. Joseph Sound is not apparent. Upper zone A is the freshwater zone; lower zone A is the brackish-water zone; and zone B is the saline-water zone.

The water quality of samples from production wells has changed during the period 1970-94. Greatest changes have occurred since the late 1980's. Elevated chloride concentrations are probably the result of direct pumping of water with elevated chloride concentrations, the upward movement of water with elevated chloride concentrations induced by well pumpage (upconing), or from lateral movement of water from the coast. Direct pumping and upconing of higher salinity waters likely are the important factors influencing water-quality changes, because lateral chloride-concentration changes occur over a distance of miles, whereas vertical changes occur of a distance of hundreds of ft.

A numerical-modeling approach was used to simulate density-dependent, ground-water flow and transport. The model was designed to be an interpretative tool used to gain an understanding of the current and future fresh- and brackish-water resources underlying Dunedin.

Numerical simulation of the aquifer-test data provided a method to estimate hydraulic properties of the permeable zones and semiconfining units by comparing simulated and observed water-level changes in the multilayered aquifer. Numerical methods have advantages over analytical solutions because numerical methods are not constrained by multiphase discharge, storage within confining units, or number of layers in the hydrogeologic system. The derived hydraulic conductivities of upper zone A, lower zone A, and zone B were 400, 100, and 100 ft/d, respectively. The hydraulic conductivities in the semiconfining units ranged from 0.1 to 0.2 ft/d and the overlying intermediate confining unit was 0.0001 ft/d.

The purpose for simulating changes in chloride concentration in water during the 25-year simulation period (1970-94) was to assess how well model results compared to historically observed chloride-concentration changes in water from the Dunedin water plant production wells. Approximately 25 years of pumpage, water-level, and chloride-concentration data in upper zone A were available for comparison. Comparisons were made between the simulated and observed chloride-concentration changes in the six water plant wells. In general, simulated and observed chloride concentrations compared favorably, especially for production wells 13 and 14. These wells are located closest to the centroid of the water plant production-well cluster. The simulated chloride-concentration trend changed significantly in the late 1980's, corresponding to a similar trend in measured chloride concentrations.

Numerical simulation also was used to estimate future trends in chloride concentration in the uppermost Upper Floridan aquifer resulting from brackish-water development. Three different pumping scenarios were simulated including a single brackish-water well away from current production wells, combined withdrawals from both upper and lower zone A in equal volumes, and combined withdrawals from both upper and lower zone A in unequal volumes. The model results indicate that pumping from lower zone A (the brackish-water zone) does not appear to negatively influence the chloride-concentration trends in upper zone A (case 1). However, chloride-concentration changes in upper zone A, indicated in cases 2 and 3 (combined fresh-water/brackish-water withdrawals), will likely occur due to the continuation of current fresh-water withdrawals from upper zone A. Simulated 30-year chloride-concentration changes in lower zone A do not appear to be affected by changes in pumping rates or volumes. However, chloride-concentration changes in lower zone A will likely occur from pumping brackish water from lower zone A.

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Appendix

Appendix. Construction data for selected wells

Well name or number	Latitude and longitude	Elevation at top of casing (feet above sea level)	Total depth (feet)	Casing depth (feet)
1	280045/824722	13.57	146	Unknown
2	280046/824709	18.38	153	56.5
3	280049/824704	27.33	149	Unknown
4	280012/824715	17.40	160	55.5
5	280032/824625	37.63	255	64.7
6	280112/824537	62.16	175	76.5
9	280114/824543	57.30	332	Unknown
10M	280139/824548	53.61	88	55.5
11	280229/824513	42.12	250	48.6
12	280229/824534	55.49	105	64.5
13	280123/824546	58.80	340	60.2
14	280123/824541	58.34	260	59.2
15	280125/824540	58.99	220	68.2
16	280125/824531	58.05	175	64.9
18M	280123/824459	48.31	243	53.0
19M	280124/824449	65.48	300	Unknown
21M	280132824500	53.69	290	Unknown
28	280028/824545	57.91	300	63.5
29	280011/824621	38.64	300	60.0
30	280010/824610	54.14	302	53.0
31	280019/824606	42.49	239	51.0
32	280031/824532	48.53	201	48.0
33	280215/824510	37.65	105	42.0
34	280126/824455	68.02	Unknown	Unknown

Appendix. Construction data for selected wells (Continued)

Well name or number	Latitude and longitude	Elevation at top of casing (feet above sea level)	Total depth (feet)	Casing depth (feet)
50	280102/824632	34.10	205	66.0
51	280249/824643	9.22	30	22.0
52	280215/824639	12.95	80	45.0
53	280114/824707	22.4	85	40
54	280015/824711	24.19	75	38
55	280217/824544	55	115	Unknown
57	280050/824534	51.14	189	Unknown
59	280020/824607	34.10	262	51
Brackish Monitor	280124/824543	59.36	465	400
Brackish Production	280123/824543	60.16	400	220
ROMP TR14-1 (Tampa/Suwannee)	280002/824126	20.18/20.19	170/284	70/264
ROMP TR14-2 (Tampa/Ocala)	280132/824528	55.22/55.37	218/460	213/440
ROMP TR14-3 (Tampa/Suwannee)	280118/824345	97.61/97.61	176/319	125/299
East Bay Country Club	275430/824607	10.78	245	Unknown
St. Catherine	275521/824443	19.80	200	150
Cove Cay	275604/824317	9.42	160	80
Clearwater-Dunedin 31	275753/824353	56.49	283	Unknown
Pinellas Deep Well 665	275815/824404	36.61	299	81
Mission Hills	275842/824303	58.27	385	47
Garden Street Triangle	275843/824742	33.44	208	54
Regency Oaks	275949/824424	92.50	305	102
USGS Deep 27	280254/824416	68.53	405	Unknown
Clearwater-Dunedin 27	275753/824337	51.06	560	523
Clearwater 67	280022/824229	69.69	297	92